CHARACTERISTIC BOND BEHAVIOR OF PRESTRESSING STRANDS WITHIN THE TRANSFER LENGTH

By

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SYMBOL	DESCRIPTION
x	distance from axis of abscissa.
d_b	diameter of strand.
ϕ	perimeter of strand.
A_{ps}	nominal area of steel section.
A_c	concrete section area.
E_{ps}	modulus of elasticity of steel.
E_c	modulus of elasticity of concrete.
S_x	total slip distribution.
S_{xs}	slip distribution due to steel alone.
S_{xc}	slip distribution due to concrete alone.
T_x	bond stress distribution.
F_{sx}, ε_{sx}	stress and strain distribution in the steel.
F_{cx}, ε_{cx}	stress and strain distribution in the concrete.
K	elastic stiffness of the bond stress-slip relation.
T_{max}	maximum plastic bond stress.
U'_t	maximum bond stress over square root of concrete strength.
U'_k	elastic stiffness over square root of concrete strength.
L_t	transfer length.
L_{te}	length of elastic zone.

L_{tp}	length of plastic zone.
f_{st}	steel stress at the end of L_{te}.
f_{si}	initial prestressing stress.
f_{se}	effective steel stress.
f'_{ci}	concrete strength at steel transfer.
M	constant for properties of concrete and steel.
K_1	constant.
A_1	constant.
B_1	constant.
A_{1s}	constant.
A_{1c}	constant.
A_2	constant.
A_3	constant.
A_4	constant.
A_5	constant.

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In prestressed concrete members, the total force of effective prestressing must be transferred to the concrete entirely through the bonding between the prestressing strand and the concrete surrounding it. The distance required to transfer the effective prestress force is called the transfer length.

The current test procedure for transfer length, which determines transfer length by measuring concrete strain, has an actual bond stress state in the member; however, it is difficult to determine the bond properties of maximum bond stress and bond stiffness with this method. It is also difficult for design engineers to understand and select a correct safety criterion from the widely distributed results of such a transfer.test alone.

An alternative testing procedure is provided here to determine the bond properties without measuring the concrete strain. In this test, bond stress is measured directly by creating a similar bond condition within the transfer length in a real beam during the transfer of prestressing force. The suggested test method generally provides reasonable bond properties within the transfer length when comparing the results with previous studies. It is suggested that this test procedure be performed with the ordinary transfer test when determining the transfer length in a prestressed, pretensioned concrete beam.

A new analytical approach is considered to understand transfer bond performance. It is based on the bond slip, bond stress, steel stress, and concrete stress distributions within the transfer length of a prestressed, pretensioned concrete beam. The bond stress increases proportionally with the slip to the limit of maximum bond stress within the elastic zone and remains at a constant maximum value within the plastic zone. The total transfer length, stresses, and slip distribution are obtained by defining the location where steel stress is zero. The average total transfer length and free-end slip obtained in the proposed analytical study generally give a close comparison to those of Cousins et al. in bare strands but 8.8 inches longer in coated strands (this study, 27.5", Cousins et al., 18.7").

CHAPTER 1

INTRODUCTION

1.1 General

Although prestressed concrete has been a popular structural material for the past several decades, its bond performance is still not well understood. As a result, the adequacy of current provisions for transfer bond lengths as listed in the American Concrete Institute (ACI-318) Code [1] and AASHTO Specifications (American Association of State Highway and Transportation Officials) [2] has come into question. Transfer length should be defined first in order to determine the total development length. A realistic estimation of the transfer bond performance of a prestressing strand also is desirable for an accurate determination of shear and flexural strength at the critical section.

1.2 Statement of Problem

The transfer bond length has been measured indirectly by the concrete strain, under the assumption that the elastic and plastic bond stress fully transfer the entire steel tensile stress to concrete compressive stress within the transfer length, even though there is a continuous and significant bond

slip between concrete and steel. Although it is generally accepted that bond stress in beam members must be determined by a transfer and development test, there still is controversy about the accuracy of such test results, even though the test has been used for the past several decades. The reasons for the varying results can be attributed to the following: 1) assumptions that neglect various factors, 2) different interpretations of data, 3) different instrumentation gauges on concrete compressive strain, and 4) different measuring time after releasing the strand.

The transfer length test uses an actual bond stress state in the member; however, it is difficult to measure it accurately. Since the bond length is basically an effect of bond stress, a reasonable estimate of bond stress, if available, may directly relate to bond length.

Bond stress has a number of influencing factors which are difficult to determine when using the ordinary transfer and development test. Several parameters--including size and type of steel; surface condition of steel; strength, confinement, and compaction of concrete around steel; cover thickness; and type of release--are believed to affect the transfer length of the strand. Insufficient knowledge of the degree of the individual and combined effects of such parameters has led to different results in the bond tests and confusion in the industry.

1.3 Scope of Work

The bond test for this study was created to obtain the bond properties directly from a rectangular prism with a single strand, as will be discussed in Chapter 3. A model with a similar bond condition within the transfer length during the transfer of prestressing force was chosen to describe the bond properties of 1/2"-diameter uncoated and grit-impregnated, epoxy-coated prestressing strands.

A new analytical method is proposed in Chapter 4 to better understand the transfer bond performance. This model uses the maximum bond stress and bond stress-slip relationships within the transfer length region. The analytical work is based on four main variables: bond stress, slip, steel stress, and concrete stress distribution along the transfer length. The following concepts are implicit in this study:

1) The maximum bond stress and bond stress-slip relationships are obtained from the test with similar boundary conditions in the beam within the transfer length.

2) The transfer length is divided into an elastic and a plastic zone. The bond stress, steel stress, slip, and concrete stress interact within the elastic zone. The bond stress increases proportionally with slip to the limit of the maximum bond stress within the elastic zone and remains at a constant maximum value within the plastic zone.

3) The entire concrete section is assumed to have a uniform compressive stress which is due to the tensile steel stress.

4) The whole transfer length, stresses, and slip distribution are obtained by defining the location where steel stress is zero due to bond stress.

1.4 Objectives

The objectives of this analytical and experimental work are as follows:

1) to suggest a new experimental model to obtain the bond properties, which are difficult to determine in ordinary transfer tests;

2) to develop a new analytical model to understand the transfer bond mechanism;

3) to study the degree of the effect of several variables on critical parameters such as free-end slip, elastic zone, plastic zone, and total transfer length; these variables are initial and effective steel stress, the loss of initial steel stress after release, maximum bond stress over the square root of initial concrete strength, initial concrete strength, bond stress-slip relationships, Young's modulus of steel, and the section area of concrete; and

4) to investigate the typical bond behavior of 1/2"-diameter coated and bare strands.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

More than 30 separate investigations have been reported in the literature concerning the bond of prestressed and pretensioned concrete beams. The major concern of this chapter is to study the bond characteristics of a seven-wire prestressing strand in a helical wrap, which is currently in use in the United States and Canada. However, the studies of Hoyer and Friedrich [3], Krishnamurthy [4], and Javor and Lazar [5] on a different seven-wire prestressing strand are also included in order to help in understanding the major concern. Over and Au [6] and Guyon [7], who used a smooth wire for their experimental and analytical models, also are considered.

Generally, the transfer and development bond studies are numerous and complex because each study had its own objectives. In this chapter, the results of previous bond studies are summarized according to their objectives.

2.2 Characteristics of Bond Stress

Hoyer and Friedrich [3] pointed out that swelling of the wire section is a major contributor to the anchorage in a prestressed, pretensioned concrete beam. This swelling, due to the loss of steel stress, develops a wedge effect during the release of the strand, thereby giving rise to a large frictional force within the transfer length. This has come to be known as the "Hoyer effect."

Janney [8] also concluded that the radial bond stress and coefficient of friction are considered to be the main factors in analyzing the transfer bond mechanism. Hognestad and Janney [9] suggested that adhesion, friction, and mechanical interlock may contribute to the bond in a pretensioned beam; the latter two are the major factors influencing bond due to the large slip at the end of the pretensioned beam.

Over and Au [6] studied the transfer bond behavior--friction and mechanical interlock--of smooth wire and seven-wire strands. They concluded that 1) after general slip, the mechanical interlock resistance causes additional stress to develop on a multiwire strand, and 2) a large difference is found in the stress patterns when comparing the data provided by gauges applied directly to the strand with that of gauges applied to a concrete prism surface. It was found that the results of strand gauges are more accurate than those of concrete gauges.

Kaar and Magura [10] studied the effects of blanketing on the transfer length and development lengths. A plastic tube was used either partially or fully at the end of the beam to prevent the bonding action. The authors suggested that the bond slippage occurs in three stages: 1) slip transfers through cracks due to flexure, 2) general bond slip occurs along the entire embedment length, and 3) mechanical interlock is destroyed. They concluded that ACI requirements are inadequate, and twice this anchorage length is needed for a blanketed strand. They also confirmed that the strand stress does not generally go down to zero after general bond slip but decreases only toward the prestress level that had been confirmed by Janney [8]. Even after general bond slip, mechanical interlocking is still enough to maintain considerable strand stress.

Deatherage and Burdette [11] conducted transfer and development length tests on 20 type I AASHTO prestressed concrete I-beams and six prisms. They confirmed that the strain distribution is not generally a solid curve but fluctuates at the end of the transfer length; thus, some variation in the measured transfer length may occur as a result of different interpretations of the data. Their conclusions regarding adhesion, friction, and mechanical interlock are considered separately as follows: 1) adhesion is

inversely related to initial strand slip, but friction increases with increasing initial strand slip; and 2) adhesion is unaffected by concrete strength, but friction and mechanical interlock increase with increasing concrete strength in the end region of the beam.

Dorsten, Hunt, and Preston [12] observed smooth imprints of wires left in a concrete pull-out test block as uncoated strands were rotated during pull-out.

In 1959, Hanson and Kaar [13] performed flexural bond tests on 47 beams with varying strand diameters and concrete cross sections. They decided that design criteria should be governed by first bond slip rather than by final bond failure. They made four observations on flexural bond. First, prior to cracking, the steel stress increases only slightly. Second, after cracking, the stresses increase abruptly at the location of the crack. Third, as the load is increased, the flexural stress moves toward the transfer region in the form of a wave. When the stress wave reaches the transfer region, a general bond slip occurs and the strand stress decreases. Finally, mechanical interlock and friction in the development length are fully provided to maintain a further increase in the substantial amount of stress on the strand after general bond slip until a flexural failure occurs.

2.3 ACI/AASHTO Transfer and Development Length

The current provisions of ACI Committee 318 [1] for development length of prestressing strands, contained in Section 12.9.1, are primarily based on the work of Hanson and Kaar [13] on flexural bond length and on the work of Kaar, Lafraugh, and Mass [14] on transfer length. The provisions for minimum development length in Figure 2.1 are stated as follows:

$$L_d = (f_{ps} - 2/3\ f_{se})\ d_b \qquad (2.1)$$

where L_d = development length (in),

f_{ps} = stress in the strand at nominal strength of the member (Ksi),

f_{se} = effective stress in the strand (Ksi),

d_b = nominal diameter of the strand (in).

The above equation can be rewritten as follows:

$$L_d = (f_{se}/3)\,d_b + (f_{ps} - f_{se})\,d_b \qquad (2.2)$$

The first and second terms represent transfer length and flexural bond length, respectively.

Transfer bond stress develops due to the initial tension and release of the strand (effective prestressing force). The length over which this effective prestressing force is delivered to the concrete is called transfer length. Flexural bond stress is mobilized as the member is subjected to bending as a result of an externally applied load. The additional

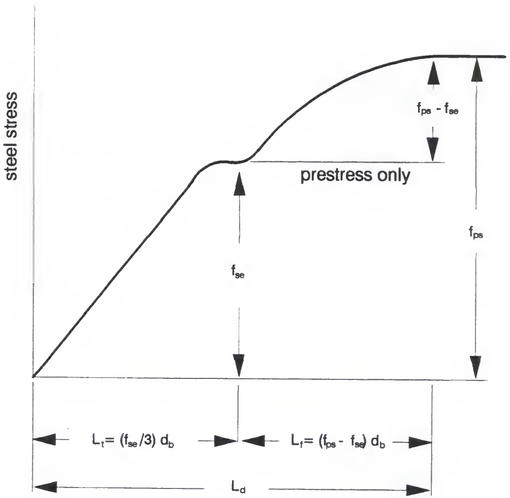


Figure 2.1 Model of ACI Equations for Transfer and Development Length.

length over which this increased stress is to be transferred is known as the flexural bond length. The sum of transfer length and flexural bond length is termed the development length. Available bond length is the sum of shear span and overhang. If the available bond length is greater than the required development length, no premature bond failure can occur.

The transfer length in Equation 2.2 will depend on effective prestress and nominal strand diameter. The denominator 3 represents a conservative average concrete strength in ksi according to Zia and Mostafa [15]. The Code also permits the transfer length to be considered as 50 d_b for strands (ACI Section 11.4.3). The underlying assumption means an effective prestress of 150 Ksi in prestressing strands. Fagundo and Narayan [16] said that the effective prestress depends on the initial prestress, f_{si}, and the amount of prestress loss; their work was based on Grade 270 strand with a 70% jacking load and a prestress loss of 20%. The second term in Equation (2.2) implies that the flexural length, L_f, is derived in terms of average bond stress, U_{ave} as $(f_{ps} - f_{se})$ $A_{ps}/U_{ave}/d_b/\pi$. This equation can be simplified as $(f_{ps} - f_{se})$ $d_b/4/U_{ave}$. Fagundo and Narayan said that it implies a value of 1 Ksi in the denominator for flexural bond length. Hence, it can be concluded that the ACI code assumes a value of 250 psi as the average value of bond stress in this zone. The above

expressions suggest that the code, by stipulating a minimum flexural bond length, ensures that the bond strength is not exceeded.

2.4 Typical Analytical Bond Studies

Several equations have been proposed for transfer bond length. The concepts, assumptions, and influencing parameters will be discussed, and the results of various equations are listed in Table 2.1.

Table 2.1 Results of Equations for Transfer Length.

Authors	Transfer length (in)			
	1/2" UN	1/2" CL	1/2" CM	1/2" CH
(1) Cousins	44.2	30.1	17.3	16.5
(2) Kaar	38.5	N/A	N/A	N/A
(3) Janney	28.5	N/A	N/A	N/A
(4) Over	35.0	N/A	N/A	N/A
(5) Dorsten	26.9	N/A	31.3	N/A
(6) ACI	30.2	29.5	30.8	29.4
(7) M&S	40.0	40.0	40.0	40.0
(8) Z&M	33.8	32.3	34.5	32.3

Source: This Table is summarized from Cousins, Johnston, and Zia [17].
(1) result from Cousins et al. [17],
(2) result from Kaar, LaFraugh, and Mass [14],
(3) result from Janney [18],
(4) result from Over and Au [6],
(5) result from Dorsten, Hunt, and Preston [12],
(6) result from ACI [1],
(7) result from Martin and Scott [19],
(8) result from Zia and Mostafa [15].

Note:
UN uncoated strand,
CL low grit-impregnated, epoxy-coated strand,
CM medium grit-impregnated, epoxy-coated strand,
CH high grit-impregnated, epoxy-coated strand.

Janney [8] first proposed that elastic analysis is not sufficient to give a good prediction for the bond in a pretensioned beam because a large part of the transfer bond length is due to friction between concrete and steel.

In 1960, Guyon [7] attempted to predict the steel stress within the transfer length region. He divided the transfer length into four zones: elastic, elasto-plastic, plastic, and bond failure zone of the concrete surrounding the bar. However, the length for the elasto-plastic zone is very short and negligible when compared with the other zone lengths. As long as the slip is small, the bond stress and slip increase linearly until attaining maximum bond stress within the elastic zone. The bond stress remains at a constant ceiling value, the maximum bond stress within the plastic zone. The stress at any point in the strand along the beam can be determined if the maximum bond stress and bond stress-slip relationship can be determined in advance for a particular strand diameter, concrete strength, and prestressing force. However, Guyon's study shows that the predetermined values of the above parameters are distributed over a wide range.

Anderson, Rider, and Sozen [20] proposed the transfer and development length as functions of the square root of the bar diameter. Horn and Preston [21] approximated the result as follows:

$$L_t = 2.4\ f_{se}\ A_{ps}\ (1.4 - .9\ d_b) \tag{2.3}$$

$$L_d = (4.25\ f_{su} - 1.85\ f_{se})\ A_{ps}\ (1.4 - .9\ d_b) \tag{2.4}$$

Zia and Mostafa [15] proposed an equation for development length based on the linear regression analysis of all the research completed before 1977. The equation for transfer length, L_t, is in the following form:

$$L_t = [1.5\ (f_{si}/f_{ci})\ d_b] - 4.6 \tag{2.5}$$

and flexural bond length, L_f:

$$L_f = 1.25(f_{su} - f_{se})\ d_b \tag{2.6}$$

where f_{si} = initial stress in strand before losses (Ksi),

f'_{ci} = concrete strength at transfer (Ksi),

d_b = diameter of prestressing strand (in),

f_{su} = ultimate stress of the prestressing strand (Ksi),

f_{se} = effective stress of the strand after losses (Ksi).

This equation takes into account the effect of concrete stress at transfer and initial prestress in addition to the effect of strand diameter and effective steel stress of the ACI equation. The resulting equation is comparable to that of the ACI for small size strands but conservative in the case of low concrete strength at transfer. However, at higher concrete strengths at transfer, it is the ACI code equation that is more conservative. Zia and Mostafa concluded that the ACI code needs an increase of 25% in flexural length.

Martin and Scott [19] in 1976 reevaluated the earlier tests performed by Hanson and Kaar [13] and proposed expressions that provide an approach to designing precast, pretensioned units for spans too short to provide an embedment length that will develop the full strength of the strand. These expressions are as follows:

for L_x less than 80 d_b:

$$f_{ps} < \frac{135}{d_b^{1/6}} + \frac{.39\ L_x}{d_b} \tag{2.7}$$

for L_x larger than 80 d_b:

$$f_{ps} < \frac{L_x}{80\ d_b}\ (\frac{135}{d_b^{1/6}} + 31) \tag{2.8}$$

where L_x = distance from the end of member to the section under consideration (in),

d_b = diameter of the strand (in),

f_{ps} = nominal stress in prestressed reinforcement (Ksi).

They suggested 80 times strand diameters as the transfer length for all strand sizes, which is much more conservative than the ACI code equation. The authors also proposed that a low degree of reliability prohibits the consideration of the effects of mechanical interlock in the design. Ghosh and Fintel [22] concluded that Martin and Scott's approach proves useful.

Cousins, Johnston, and Zia [17] proposed the following equations from their analytical studies. The maximum bond stress over the square root of concrete strength, U'_t, for the plastic zone and bond stress-slip relationships, B, for the elastic zone are presented in this work.

For transfer length, L_t:

$$L_t = \frac{(.5\,U'_t\sqrt{f'_c})}{B} + \frac{f_{se}A_{ps}}{(\pi\, d_b U'_t\sqrt{f'_c})} \tag{2.9}$$

The first term represents the elastic zone and the second term represents the plastic zone within the transfer length.

For flexural bond length, L_b:

$$L_b = \frac{(f_{ps} - f_{se})\,A_{ps}}{\pi\, d_b U'_d\,\sqrt{f'_c}} \tag{2.10}$$

where A_{ps} = area of steel (in²),

d_b = nominal diameter of prestressing strand (in),

f'_{ci} = compressive strength of concrete (psi),

f_{se} = effective prestress in transfer after loss (psi),

B = bond modulus (psi/in),

U'_d = flexural bond stress (psi),

U'_t = plastic transfer bond stress (psi).

2.5 Typical Studies on Free-End Slip

The free-end slip has been considered as another critical factor in bond length. A theoretical expression in Equation 2.11 was derived by Krishnamurthy [4], relating the transfer length (transmission length) to the free-end slip as follows:

$$L_t = \sqrt{\frac{\Delta_o}{K}} \tag{2.11}$$

where L_t = transfer length (cm),

Δ_o = slip at the free-end ($1/10^3$ cm),

K = factors obtained from the size of strand.

The free-end slip, Δ_o , was obtained from various factors such as the diameter of strands, concrete strength, prestressing forces, and method of transfer, which were examined using the data obtained by other investigators.

Anderson and Anderson [23] performed flexural bond test on 36 pretensioned hollow-core slabs. They suggested that transfer and flexural bond quality are directly related to the amount of free-end slip. The average strand stress, which is related to the free-end slip, is assumed as one-half of initial steel stress, f_{si}. Transfer length is obtained as $L_t = 2\ \Delta_s\ E_{ps}/f_{si}$, which is obtained from the stress-strain relationship, $\Delta_s\ /\ L_t = f_{si}\ /\ 2\ E_{ps}$. The ACI transfer length equation is given as $L_t = f_{se}\ d_b\ /3$. Thus,

$$\Delta_s = \left(\frac{f_{se}}{3}\right) d_b \frac{(f_{si})}{2E_{ps}} \tag{2.12}$$

where Δ_s = slip at free-end (in).

They computed the allowable strand slip as 0.031" to 0.094", according to the size of the strand.

Brooks, Gerstle, and Logan [24] in 1988 formulated a theory referred to as the "slip theory" from a combination of the theory of bilinear transfer stresses, proposed by Anderson and Anderson [23], and the bilinear strand development diagrams proposed by Robert F. Mast [25]. A direct relation of the bond quality of the concrete to the initial end slip of the strand is proposed in this theory. The authors derived the following equations:

for transfer length, L'_t:

$$L'_t = 2\delta E_{ps}/f_{si} \tag{2.13}$$

for flexural bond length, L'_b:

$$L'_b = (f_{ps} - f_{se})\ L'_t/f_{se} \tag{2.14}$$

where δ = measured initial strand slip at the end (in),

E = modulus of elasticity of the strand (psi),

f_{si} = initial stress in the strands at transfer (psi),

f_{ps} = nominal stress in the strands (psi),

f_{se} = effective stress in the strands after losses (psi).

2.6 Bond Stress-Slip Tests

Bond stress-slip tests on prestressing strands have been conducted by Edwards and Picard [26], Stocker and Sozen [27], Brearly and Johnston [28], and Cousins, Badeaux, and Mostafa [29]. Edwards and Picard, Stocker and Sozen, and Brearly and Johnston conducted pull-out tests on prestressing strands; however, these results are considered to be irrelevant to the actual bond within the transfer length because they do not consider the Hoyer effect on steel. The results of bond stress-slip tests are listed below in Table 2.2.

Table 2.2 Results from Bond Stress-Slip Tests.

Strand Diameter and Coating	(1) Edwards U'_t (psi)	(2) Brearly U'_t (psi)	(3) Cousins U'_t (psi)
1/2" UN	4.80	3.81	7.0
1/2" C	N/A	12.35	17.0

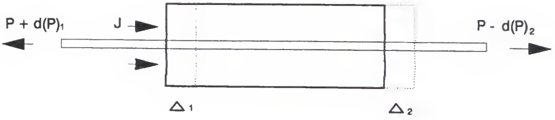
Source: (1) result from Edwards and Picard [26],
(2) result from Brearly and Johnston [28],
(3) result from Cousins, Badeaux, and Mostafa [29].
Note: C grit-impregnated, epoxy-coated strand,
UN bare strand.

Edwards and Picard [26] obtained bond stress-slip relations from six pull-out specimens and six tensile bond specimens. They performed tests to predict the flexural crack widths in a pretensioned beam. Relatively thin covers of 0.5, 1.0, and 1.5 inches were chosen to get the uniform bond stress

distribution within the specimens. Special instruments and test procedures were adopted for thin specimens. The conclusion reached was that up to the point of critical slip, the bond stress-slip relation increased almost linearly, and for further increases in slip, bond stress remained a constant maximum value, provided no longitudinal crack appeared in the specimen.

Brearly and Johnston [28] conducted 52 direct tension pull-out tests on 8" x 8" cross section and 12"-long specimens. These specimens were made with 3/8"-, 1/2"-, and 0.6"-diameter bare and coated strands. The coated strands were tested with three grit densities: low, medium, and high. They confirmed that the proposed test could not produce the same bond stress in beam members. They described the results as an indicator for regulating the bond quality control. They concluded that 1) a grit impregnated epoxy-coated strand has a larger bond stress capacity than uncoated strand, 2) grit density is a very important factor for bond capacity, and 3) a coated strand without grit has virtually no bond strength.

Cousins et al. [29] suggested a particular test method for prestressing strands which can also measure the Hoyer effect. As shown in the free-body diagram presented in Figure 2.2, this test reproduces the swelling of the strand within



J = jacking force

P + d(P)1 = increased steel force due to jacking force

P - d(P)2 = decreased steel force due to jacking force

△1 = displacement and elastic shortening of block

△2 = displacement of block

Figure 2.2 Free-body Diagram Suggested by Cousins et al.

the transfer length of a pretensioned concrete beam. The specimen size for the test was 8" x 8" in cross section and 12" long. The loading side length over the strand swelling side length of steel was chosen as 5. The average maximum bond stress, T_{max} , for a 1/2"-diameter coated strand is 450 psi to 1170 psi and for bare strand is 500 psi to 370 psi. The U'_t value, which is equal to T_{max} divided by the square root of f'_c, has an average of 17.0 for coated and 7.0 for a bare strand. They concluded that the results of the test are comparable to those of the pull-out test, but the bond stress in a specimen with the Hoyer effect is higher than that in a specimen tested by the pull-out method.

2.7 Influencing Factors

2.7.1 Size and Type of Strand

Over and Au [6] studied the transfer length of smooth wire and seven-wire strands with various diameters. They concluded that larger diameter strands required a longer transfer length than smaller diameter strands, as shown in Table 2.3. The transfer length for seven-wire strands is less than that for single wires of equal strength and stress.

Table 2.3 Transfer Length of Uncoated Strands.

Strand Diameter (in)	Concrete Strength (psi)	Size of Prism (in)	f_{se} (Ksi)	Transfer Length (in)
1/4 seven	4,900	3 x 3 x 60	164	20
3/8 seven	4,180	3 x 3 x 60	160	30
1/2 seven	5,500	3 x 3 x 80	170	35
1/4 single	4,720	3 x 3 x 60	192	29

Source: Over and Au [6].

Table 2.4 Transfer Length of Coated and Uncoated 1/2"-Diameter Strands.

Strand Type	Type of Release	Number of Tests	Transfer Length (in)	
			Initial	14 Months
Bare	Gradual	4	26.3	33.0
	Sudden	4	27.5	33.5
Coated	Gradual	3	33.3	35.0

Source: Dorsten et al. [12].

The epoxy-coating was smooth before the early 1980s, and that presented some problems with transfer and development lengths. Grit-crushed glass (samall aluminum oxide particle) was impregnated (by the Florida Wire and Cable Co.) into the epoxy-coating to improve its bonding capabilities. Dorsten, Hunt, and Preston [12] evaluated the transfer lengths of pretensioned beams with three bare strands and four grit-impregnated epoxy-coated strands (Table 2.4). The results for average transfer length (gradual release) immediately after

transfer as shown in Table 2.4 are 33.3" for beams with coated strands, but 26.3" for those with bare strands. They also stated that the transfer length for bare strands was 3% longer than that for the coated strands at a period of 14 months after releasing.

Cousins, Johnston, and Zia [17,30,31,32] conducted tests on 60 pretensioned prisms with bare, epoxy-coated, and grit-impregnated epoxy-coated strands of varying diameters. The measured transfer length and free-end slip shown in Tables 2.5 and 2.6 are cumulative slip at the free end for one day.

The following conclusions were reached for coated and bare strands by Cousins et al.:

1) The transfer length of a grit-impregnated, epoxy-coated prestressing strand is shorter than that of an uncoated strand of the same diameter. The grit-impregnated strand has a shorter transfer length than the ACI requirement, while the bare strand does not meet the code.

2) The measured slip for a bare strand is considerably greater than that of a grit-impregnated, coated strand.

3) Longitudinal splitting can occur due to high bond stress in an epoxy-coated strand. Some splitting problems may be encountered in members with a thin element, close strand spacing, thin cover, or poor confinement.

4) The coated strand should be handled in a manner so as to avoid damage to the coating or grit.

Table 2.5 Transfer Length of Uncoated, and Medium and High Coated 1/2"-Diameter Strands: Prism Tests.

Beam End	Ave. f'_{ci} (psi)	Ave. f_{se} (Ksi)	Ave. T_{max} (psi)	Ave. U'_t (psi)	Ave. K lb/in^3	Ave. L_t Meas. (in)	Ave. L_t Calc. (in)
T5UN	4110	181.1	286.3	4.5	288	62.5	41.4
S5UN	4420	198.5	400.1	6.0	N/A	50.8	44.5
T5CH	4110	185.0	1166	18.2	330	16.0	19.1
T5CH	4110	176.1	1191	18.6	193.5	16.1	18.0

Source: Cousins et al. [17].
Note: T5UN: concentrated, uncoated, 1/2"-diameter strand,
S5UN: eccentric, uncoated, 1/2"-diameter strand,
T5CM: concentrated, medium coated, 1/2"-diameter strand,
T5CN: concentrated, high coated, 1/2"-diameter strand.

Table 2.6 Average One-Day End Slip of Uncoated, and Medium and High Coated 1/2"-Diameter Strands: Prism Tests.

Beam End	f_{si} (Ksi)	Prestress Losses (Ksi)	Ave. 1-Day End Slip Measured (in)
T5UN	204.6	23.6	0.252
S5UN	N/A	N/A	N/A
T5CM	208.3	23.3	0.046
T5CH	196.8	20.0	0.044

Source: Cousins et al. [30,32].

Lane [33] tested for transfer length of prestressed concrete specimens of 4" x 4" to 9" x 9" in cross section and 12' long with single or four strands (Table 2.7). She concluded the following: 1) The transfer lengths for bare strands were approximately 1.6 times the transfer lengths of epoxy-coated strands. 2) The transfer lengths for specimens containing four strands were 25% greater than those for specimens containing one strand in both bare and coated 3/8" and 1/2" diameter strands.

Table 2.7 Transfer Length of Coated and Uncoated Strands.

Str. Dia. (in)	Average (in)				$(f_{se}$ D) / 3 (in)	
	Uncoated		Epoxy-coated			
	One Strand	Four Strands	One Strand	Four Strands	One Strand	Four Strands
3/8	26.9	33.7	16.8	21.6	21.7	19.6
1/2	33.0	40.0	20.2	26.0	26.5	25.7
0.6	43.2	>72.0	26.0	26.2	31.7	31.0

Source: Lane [33].

2.7.2 Surface Condition of Steel

Janney [18] attempted to define the bond characteristics within the transfer length in a pretensioned concrete beam. Single pretensioned prism specimens, 2" x 2" in cross section and between 72" and 96" long, were chosen for tests with variable surface conditions--clean, rusted, and lubricated. In Table 2.8, the transfer length average is 24" for a rusted strand and an average of 33" for a clean strand.

Table 2.8 Transfer Length of Uncoated 1/2"-Diameter Strands.

Ultimate Strength (Ksi)	Surface Condition	f_{se} (Ksi)	f'_{ci} (psi)	Transfer Length Measured (in)
270	Clean	175.8	4,115	33
270	Rusted	175.8	4,090	24
250	Clean	150.0	4,200	28

Source: Janney [18].

Hognestad and Janney [9] also suggested that the transfer of stress between steel and concrete is much more rapid in a rusted wire than in a clean wire.

Kaar, Hanson, Corley, and Hognestad [34] studied the effects of the surface condition of a 3/8", 270 Ksi prestressing strand for sudden and gradual release (Table 2.9). The following surface conditions were used: sandblasted, lightly rusted, and smooth. A considerably scattered distribution in results was obtained. The results showed that a greater decrease in transfer length was obtained for a slightly rusted and sandblasted strand than for a smooth strand, and for a gradual-release strand than for a sudden-release one.

Table 2.9 Transfer Length of Uncoated 3/8"-Diameter Strands.

Surface Condition	Type of Release	Number of Tests	Transfer Length (in)		
			Low	Ave.	High
Smooth	Gradual	39	12	23.9	39
Smooth	Sudden	37	17	29.2	54
Sand Blasted	Sudden	15	11	18.6	28
Slightly Rusted	Sudden	12	9	14.2	23

Source: Kaar, Hanson, Corley, and Hognestad [34].

Hanson [35] used 14 prestressed concrete prisms to determine the effect of surface roughness. Clean "as received," partially rusted, rusted, and deformed 7/16"-diameter strands were used for bond performance. Hanson determined that the rusted strand and deformed strand showed an average 30% improvement in transfer length over a clean "as received" strand.

Deatherage and Burdette [11] conducted transfer and development length tests on 20 type I AASHTO prestressed concrete I-beams (Table 2.10) and six prisms (Table 2.11). The prestress force was transferred when the concrete compressive strength reached a minimum of 4000 psi by frame cutting (sudden release). Mechanical strain gauges were used to measure the transfer length along the neutral axis and the center of gravity of the steel. Fifteen gauge points equally spaced at 5" (125 mm) were chosen. Transfer length was

measured as an average 42.8" for a 1/2"-diameter clean strand and an average 34" to 36.5" for a 1/2"-diameter weathered strand. The transfer lengths of uncoated and clean 1/2"-diameter strands from AASHTO beam tests (Table 2.10) showed comparable to those from prism tests (Table 2.11).

Table 2.10 Transfer Length of Uncoated 1/2"-Diameter Strands: AASHTO Beam Tests.

Beam	Surface	f'_{ci} (psi)	f_{si} (Ksi)	f_{se} (Ksi)	Ave. Measured L_t (in)
5-1&2	Clean	4,000	202.5	187.1	42.8
5-3	Weathered	4,775	202.5	190.0	34.0
5-4	Weathered	5,225	202.5	191.5	36.5

Source: Deatherage and Burdette [11].

Table 2.11 Transfer Length of Uncoated 1/2"-Diameter Strands: Prism Tests.

Prism	Dimension (in)	f'_{ci} (Ksi)	f_{si} (Ksi)	Ave. Measured L_t (in)
P1&2	3.5 x 3.5 x 144	4,757	175.0	37.3
P5&6	3.75 x 3.75 x 144	4,757	202.5	42.8

Sources: Deatherage and Burdette [11].

2.7.3 Confinement and Compaction on Steel

Anderson and Anderson [23] concluded that a poor consolidation of concrete around the strands was the primary cause for premature failure and free-end slip.

Javor and Lazar [5] measured the transmission length of concrete prisms with a single 15.5 mm-diameter, seven-wire strand. The dimensions of the prisms were 11 x 11 x 400 cm. They determined that the bond strength depends mainly on the quality of cement mortar surrounding the strand. It was found that the density of concrete is a major influencing factor, while concrete strength is not an important factor. The degree of density of concrete is obtained by the intensity of vibration and concrete consistency.

2.7.4 Type and Amount of Release

High-strength strands require a greater transfer length because of a higher initial prestressing force, a conclusion reached by Janney [18] (Table 2.8).

The tests of Kaar et al. [14] included varying strand diameters and varying concrete strengths and sections (Table 2.12). The ultimate strength of strands was between 253 Ksi and 275 Ksi, and the effective stress immediately after release was between 0.58 f_{pu} and 0.72 f_{pu} . Whittemore gauges and brass discs were embedded in the concrete to measure strain. The gauge readings were recorded at 1, 3, 7, 14, 28, 56, 90, 180, and 365 days. Kaar et al. concluded that the sudden release ends exhibited a 20% greater transfer length than the gradual release ends for a 1/2"-diameter strand and 30% for a 0.6"-diameter strand.

Table 2.12 Transfer Length of Uncoated Strands.

Strand Diameter (in)	Concrete Strength (psi)	Type of Release	Transfer Length (in)		
			1 Day	28 Days	365 Days
3/8	4,170	Sudden	N/A		
		Gradual	N/A		
	5,000	Sudden	25.5	26	27.5
		Gradual	20	23	25.5
1/2	4,170	Sudden	37	35.5	37.5
		Gradual	34	34	38
	5,000	Sudden	41	42	44
		Gradual	34	36.5	37.5
0.6	4,170	Sudden	39	38.5	40.5
		Gradual	31.5	32.5	33.5
	5,000	Sudden	39.5	40.5	39
		Gradual	28.5	30	32

Source: Kaar et al. [14].

The tests showed that the transfer length of a 3/8"-diameter strand was proportional to the effective steel stress between 120 Ksi and 165 Ksi (Table 2.13).

Cousins et al. [17] stated that the sudden release of a prestressing strand increases the transfer length approximately 8% more than the gradual release.

Table 2.13 Transfer Length of Uncoated 3/8"-Diameter Strands.

Specimen Size & f'_{ci}	Type of Release	f_{se} (Ksi)	Transfer Length, (in)		
			at transfer	7 days after	28 days after
3/8-3330e	Gradual	120	12	13	12
3/8-3330d	Gradual	140	15	16	17
3/8-3330c	Gradual	165	21	22	23
3/8-3330e	Sudden	120	23	23	23
3/8-3330d	Sudden	140	26	26	26
3/8-3330c	Sudden	165	32	32	31

Source: Kaar et al. [14].

2.7.5 Initial Concrete Strength

Kaar et al. [14] studied the influence of concrete compressive strength at the transfer of prestressing force on the transfer length of strands. They concluded that the variation of concrete strength from 1,500 to 5,500 psi had little influence on the transfer length of clean strands up to 1/2"-diameter (Table 2.12), and that for a 0.6"-diameter strand, by using a frame-cutting process, the transfer length was reduced with an increase in concrete strength.

However, Deatherage and Burdette [11] concluded that the transfer length decreases slightly with increasing concrete strength (Table 2.10). In reinforced concrete, the bond stress has been regarded to be approximately proportional to the square root of the concrete strength, as is the modulus of

rupture. The analytical study of Cousins et al.[17] suggested that bond stress is proportional to the square root of initial concrete strength at the time of transfer up to the plastic bond stress, U_t, within the elastic zone. They stated that the plastic bond stress can only be obtained experimentally. However, the term for plastic bond stress, $U_t=U'_t(f'_{ci})^{1/2}$, represents the concrete strength effect for the elastic and plastic zones. They did not test for the concrete strength effect.

2.7.6 Time and Heat

Hognestad and Janney [9] proposed that the transfer bond stress capacity may be considerably affected by time, fatigue, impact, and vibration.

Kaar et al. [14] concluded that an average increase of 6% was observed in the transfer length over a period of 365 days after prestress transfer (Table 2.6).

In 1992, Shahawy, Issa, and Batchelor [36] investigated transfer length in a full-scale AASHTO pretensioned beam for shielded and unshielded strands. The transfer length was measured in accordance with the percentage of transfer. The strain gauge readings were recorded every two hours for two days upon the complete release of prestressing force on the concrete. Concrete strain was measured along the centroid of strands by using a 2.5"-long ERSG gauge with a 6" interval.

Transfer length was determined roughly as 30" for uncoated strands. They observed no significant changes in the measured transfer length for 48 hours after transfer.

Cousins et al. concluded [30] that the transfer length of coated and uncoated strands is not affected until the temperature reaches 156°F.

2.8 Summary of Literature Review

According to the ACI, premature bond failure cannot take place when an adequate end anchorage length is provided for a strand. However, the reasons for bond failure are not well understood, as shown in the recent test results of Kaufman [37] and Kaufman and Ramirez [38]. According to Kaufman and Ramirez, minor shear cracks within the transfer length generally lead to a bond failure of the strands and result in an overall failure in beams, even though the beams satisfy the ACI bond length requirements. Similar conclusions have been reached by Maruyama and Rizkalla [39], who recommend that "the development length for the strands should be measured from the point where major shear cracks intersect prestressing strands rather than the maximum moment location as recommended by the code" (p. 497). They agreed that a beam designed according to ACI provisions (development length requirements) can result in premature bond failure.

A recent experimental study by Cousins et al. [17] showed a 41% to 65% greater increase in transfer length of an uncoated seven-wire prestressing tendon than that of the ACI requirement, and a 16% to 63% decrease in coated tendon. Another recent test result on bare strands by Shahawy et al. [36] concluded that the current ACI and AASHTO provisions appear to be inadequate but closely comparable. Consequently, it is very difficult for a design engineer to understand and select a correct safety criterion for transfer length.

The variation of the test results in Table 2.14 obtained by measuring concrete strain on a beam show that an ordinary transfer length test does not give a satisfactory explanation of the transfer length and its behavior. The values of U'_t are roughly calculated by assuming that the bond stress is uniform maximum bond stress within the total transfer length.

Transfer length and maximum bond stress in a pretensioned concrete beam are generally obtained in an indirect way by measuring concrete strain along the centroid of steel in the member. Several parameters, including size and type of steel; surface condition of steel; strength, confinement and compaction of concrete around steel; cover thickness; and type and amount of release are believed to affect the transfer length of the strand. The transfer length test has an actual bond stress state in the member; however, measuring it is a problem. Insufficient knowledge of the individual and

Table 2.14 Comparison of Results of Previous Transfer Length Tests of 1/2"-Diameter Strands.

Diameter & Surface Cond.	Type, Release		f'_{ci} (psi)	Ave. L_t (in)	U'_t (psi)
(1) Janney 1963	1/2 U, CL		4,115	33.0	8.1
	1/2 U, RU		4,090	24.0	11.2
(2) Kaar 1963	1/2 U, G		4,170	34.0	7.8
	1/2 U, G		5,000	34.0	7.1
	1/2 U, S		4,170	37.0	7.1
	1/2 U, S		5,000	41.0	5.9
(3) Over, 1965	1/2 U		5,500	35.0	5.6
(4) Dorsten 1984	1/2 U, G		4,000	26.3	11.1
	1/2 U, S		4,000	27.5	10.6
	1/2 C, G		4,000	33.3	8.7
(5) Deatherage 1990	1/2 U		4,000	42.8	6.7
(6) Cousins 1991	1/2 U, S		4,110	62.5	4.4
	1/2 CM, G		4,110	16.0	17.8
	1/2 CH, G		4,110	16.1	16.6
(7) Shahawy 1992	1/2 U		5,110	30.0	7.4
(8) Lane 1992	1/2 U	One strand	4,330	33.0	7.1
		Four strands	4,330	40.0	5.7
	1/2 C	One strand	4,330	20.2	11.7
		Four strands	4,330	26.0	8.8

Source: (1) Janney [18], (2) Kaar et al. [14],
(3) Over and Au [6], (4) Dorsten et al. [12],
(5) Deatherage and Burdette [11], (6) Cousins et al. [17,30,32],
(7) Shahawy et al. [36], (8) Lane [33].

Note: U - uncoated strand, C - epoxy coated strand,
CH - high coated strand, CL - light coated strand,
CM - medium coated strand,
RU - rusted and uncoated strand,
G - gradual release, S - sudden release.

combined effects of such parameters has led to false results in the bond tests and confusion in the industry.

The transfer length test can be performed with an actual bond stress state in the member; however, the following questions cannot be answered clearly based on the literature review:

1) The measured concrete strain has been accepted as the same in pattern as the steel strain. The validity of this assumption has been verified by Over and Au [6] by measuring the steel and concrete strain in 3" x 3" cast-in-place prisms of lengths up to 80". Over and Au concluded that a considerable difference in stress distribution and transfer length is found by comparing the data provided by gauges applied directly to strands to those of gauges applied to a concrete prism surface. They found that data obtained from strand gauges are more accurate. Guyon [7] questioned the efficiency of the ordinary transfer test method, since bond stress in a prestressed concrete beam is in a state of compression and hence may not be tested in the same way as a bond in tension.

2) Deatherage and Burdette [11] said that the transfer length is defined as the minimum distance from the end of the beam to the point where the concrete strain curve reaches the constant strain. As an example, measuring concrete strain with a 4-inch long strain gauge with a 6-inch interval can

easily overestimate or underestimate the bond length by 6 to 12 inches because the strain distribution is not generally a solid curve but fluctuates at the end of the transfer length (elastic zone). Thus, Deatherage and Burdette [11] mentioned "some variation in the measured transfer length may occur as a result of different interpretations of the data" (p. 32). This phenomenon has been observed in the recent work by Shahawy et al., and the transfer length results of girders A1-00-R/2 and A1-00-M ([36] p.89) show that the transfer length can be defined as either 30 inches or 50 inches for 1/2"-diameter bare strands.

3) Bond stress is influenced by a number of factors, as mentioned before, and their effects should be known clearly. As an example, the concrete strength effect on transfer length has not been clearly understood.

4) The end slip has been regarded as a critical factor in determining the bond state; however, the slip pattern and bond deterioration due to large slip at the end of the beam have not been studied extensively.

A bond stress-slip test model should have similar bond conditions to those of a portion of the beam within the bond length during the transfer of prestressing force. The following drawbacks in the tests performed by Cousins et al. [29] have been eliminated in the proposed test described in Chapter 3:

1) The bond stress-slip model is developed for modeling the bond state within the transfer length. Only the elastic zone in the transfer length is governed by the bond stress-slip relationship. The steel stress decreases while bond stress rises starting from zero in this elastic zone (Figure 2.3). However, in the work of Cousins et al., the test was conducted with both the steel and bond stress at an initial condition of zero.

2) In the work of Cousins et al., the relative movement of a concrete block was measured while the steel was fixed by applying the jacking force directly to the block. In this proposed test, the relative steel movements are measured, while the concrete is fixed, by controlling the steel force at the end of the frame; thus, the same effect for the releasing of strands as in a real beam is obtained, in addition to considering the Hoyer effect. The steel stress always decreases; thus, the increase in the steel section will not cause any seating loss at the anchorage.

3) Specimens 12" to 24" long are too long to satisfy the average bond stress assumption for the bond stress-slip test. For such specimens, the bond stress cannot be assumed to be uniform as in the case of short specimens.

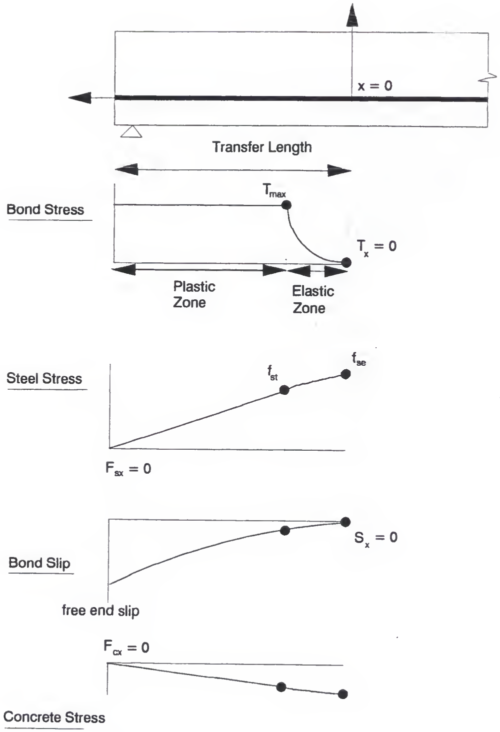


Figure 2.3 Transfer Bond Stress Model.

CHAPTER 3

TEST PROGRAM

3.1 Introduction

A new test method was proposed to better understand the bond performance within the transfer length. The maximum plastic bond stress and bond stress-slip relationship within the transfer length were determined from this test method. A model with a similar bond condition within the transfer length in a real beam during the transfer of prestressing force was chosen to describe the bond properties in a bare and a coated, 1/2"-diameter, prestressing strand.

The type and size of strands chosen for tests were 1/2" coated and bare strands. The 1/2" bare strand has shown the most variable transfer lengths in past transfer tests. The 1/2" coated strand is a new product developed after 1986 and shown to be more efficient in bond length. The transfer lengths of these two types of strands is not clearly understood.

3.2 Fabrication and Assembly

The test frame is shown in Figure 3.1. Before the main test, prestressing force was applied from the actuator. The

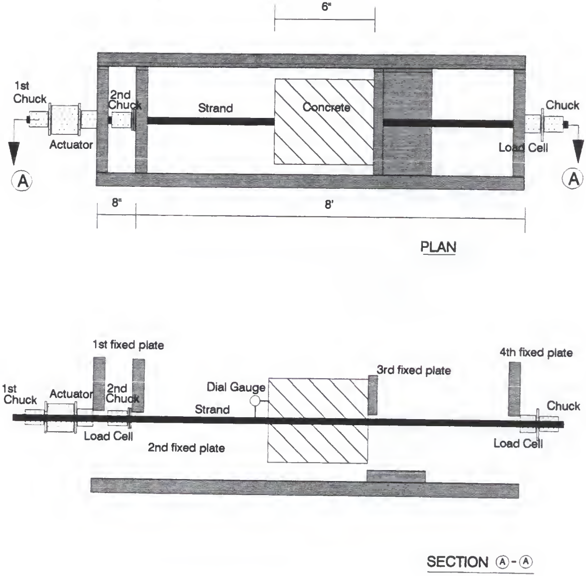


Figure 3.1 Prestressing Test Frame. Not to Scale

concrete was then cast in the test frame. After the concrete hardened, the second chuck was removed by applying an additional minimum force from the actuator. The application of this force did not effect the bond since a bond breaker (oil) was placed on the third fixed plate to prevent adhesion between the plate and the concrete (Figures 3.2 a and b). During the main test, the prestressing force was released step-by-step from the actuator (Figure 3.1). From the free-body diagram in Figure 3.2 c, the release of the force induces a swelling of the strand at the unloading side of the concrete block, a bonding force in the block, and a bond slip of the strand toward the fixed side of the block. This slip caused a reduced force at the fixed side of the load cell (Figure 3.2 c). The bonding force was the difference between the load measured in the two load cells. A step-by-step reduction of forces (200 lb for bare strand; 300 lb for coated strand) was conducted from the actuator after the slip movement reached nearly zero. The force difference in the two load cells and the slip were recorded until the point of general bond slip. The general bond slip was defined by observing an abrupt slip which was greater then 0.01". The bond stress was assumed to be uniform within a short embedment length.

The concrete prisms were cast in reusable and waterproof wooden forms (Figures 3.3 and 3.4). The prisms were consolidated by means of external vibration on the form, by

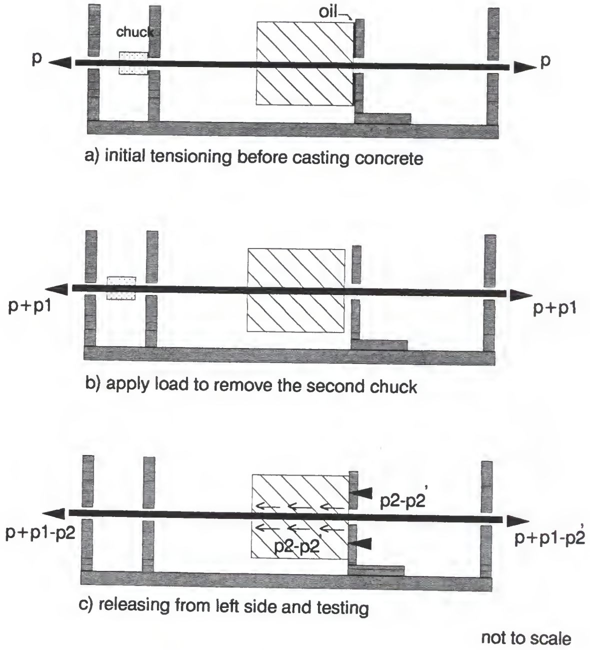


Figure 3.2 Free-body Diagram of Concrete block.

Figure 3.3 View of Form (I).

Figure 3.4 View of Form (II).

striking the strand at each side of the concrete form ten times, and were stripped after an average of 16 hours of steam curing. The prisms were cooled down to normal temperature after the steam curing in order to avoid any temperature effects on the bond. Three cylinders were also placed in the same environment with a prism (Figure 3.5) to accomplish the compression tests on them (Figure 3.6).

Using this test procedure, the prestressing strand was spun within the concrete specimen in accordance with the wedge effect in a real beam. In this test, the friction between the chuck and jack (Figure 3.7) was minimized by lubricating the inter-surface as shown.

3.3 Specimens

The assumption of uniform bond stress requires that the length of the specimen be short. Edwards and Picard [26] recommended short embedment length specimens for the assumption of average bond stress distribution in their pull-out test. Edwards and Picard adopted 0.5", 1.0", and 1.5" as lengths of specimens. Eligehausen, Popov, and Bertero [40] used five times the steel diameter for their bond test of reinforced steel. A coated strand has shown a much larger bond stress and slip than a bare strand. The specimen size and unloading rate were selected as shown in Table 3.1.

Figure 3.5 Three Cylinders for Test.

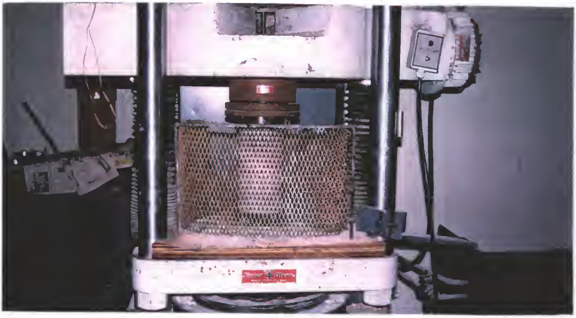


Figure 3.6 Compression Test on Cylinder.

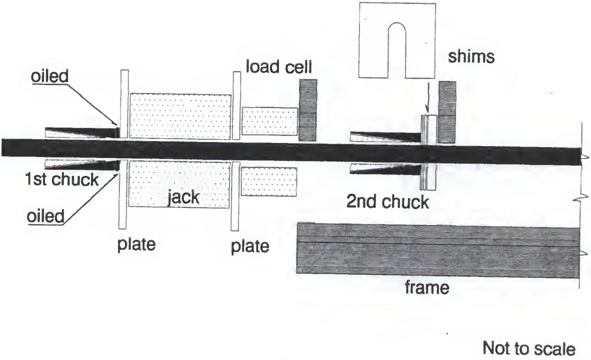


Figure 3.7 Shims for Minimum Seating Loss.

Table 3.1 Specimen Size and Unloading Rate.

Size and Type of Strand	Specimen Size height x depth x length	Unloading Rate
1/2", uncoated	6" x 6" x 6"	200 Lb/step
1/2", coated	6" x 6" x 6"	300 Lb/step

The cross-sectional dimension of the specimens is also an important factor. It is generally assumed that confinement on steel can be achieved either by stirrup or sufficient cover. The cross-sectional dimension should be deep enough to prevent cracking due to radial tension. The cross sections of 6" x 6" for uncoated and coated strands were selected because they have been determined to be sufficient to resist radial tension stress, according to preliminary test results obtained by Cousins et al. [29].

3.4 Materials

Seven-wire, 1/2"-diameter uncoated and grit-impregnated epoxy-coated, 270 Ksi guaranteed ultimate tensile strength, low-relaxation strands were used in this test (Figures 3.8 and 3.9). The prestressing steels conformed to American Society for Testing and Materials (ASTM) Standard A416 [41] and A882 [42]. The average coating thickness of coated strands provided by Florida Wire and Cable Co. products was 0.036". The modulus of elasticity of the strands was an average of 28,600 Ksi.

Figure 3.8 View of Coated Strand at End.

Figure 3.9 View of Coated and Bare Strand.

The concrete mix was designed to attain 5000 psi compressive strength in one day with steam curing (Figures 3.10 and 3.11). Table 3.2 shows the concrete mix proportions used. The mixing water amount*1 was variable for the different concrete strengths. Type II, moderate sulfate resistant Portland cement was used. Chemical additives were not used. The maximum size of coarse aggregate was 0.375". The fineness modulus of sand was 2.02. The 28-day compressive strength was determined to be in excess of 6,000 psi.

Table 3.2 Concrete Mix Proportioning.

Materials	Weight, $(yd)^3$		Volume, $(ft)^3$
	*2Dry, Lb	*3NMC, Lb	
Air	0.0	0.00	0.81
Cement	940.82	940.82	4.79
*1Water	378.98	398.89	6.07
Fine aggregate	1147.18	1148.33	7.27
Coarse aggregate	1278.29	1279.57	8.07

Note: *2Dry - materials with a dry condition,
*3NMC - materials with a natural moisture content.

3.5 Instrumentation

Two center-hole load cells were used (Figures 3.12 and 3.13) to measure the load on each side of the specimens. These two load cells were connected separately to a power supply and a multimeter (Figure 3.14). Figure 3.15 shows the calibration of the load cells. The results of the calibration are shown in Figure 3.16.

Figure 3.10 Preparation for Steam Curing (I).

Figure 3.11 Preparation for Steam Curing (II).

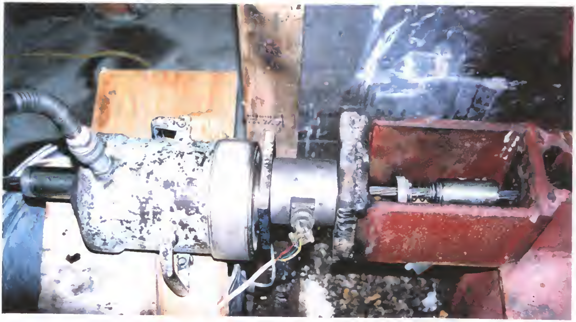


Figure 3.12 Installation of Load Cell and Actuator at Unloading Side.

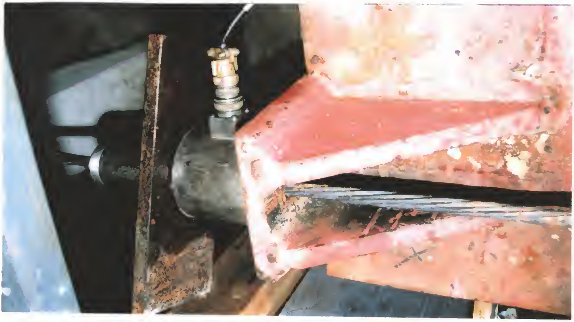


Figure 3.13 Installation of Load Cell at Fixed Side.

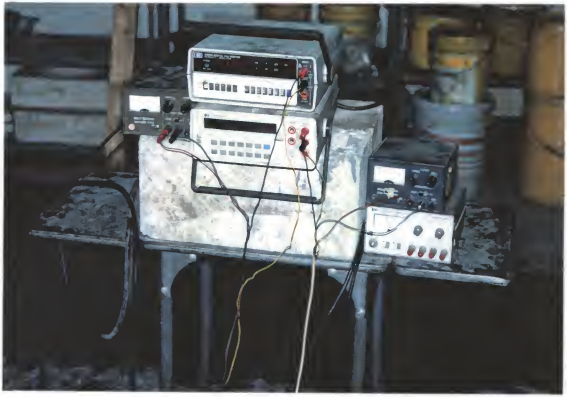


Figure 3.14 View of Power Supply and Multimeter.

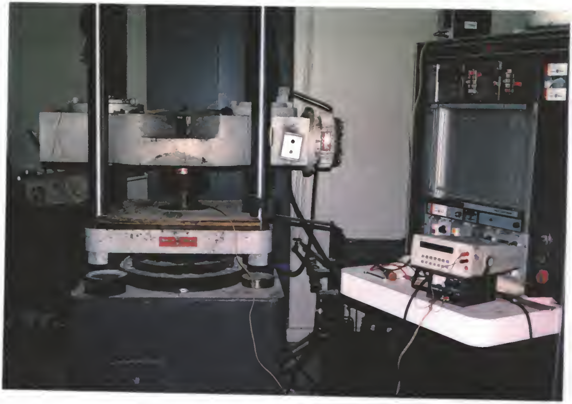


Figure 3.15 Calibration on Load Cells.

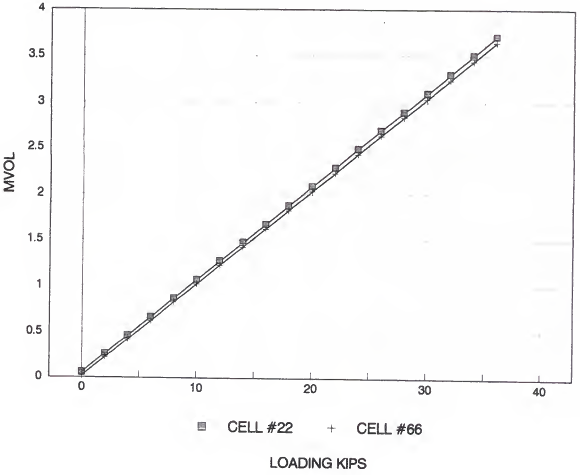


Figure 3.16 Outputs of Calibration.

The prestressing force was applied by a handpump (Figure 3.17) into the center-hole actuator. Two V-8 Enerpac needle valves (Figure 3.18) were installed between the actuator and handpump to control the whole unloading procedure. One valve controlled the unloading speed, the other the amount of unloading.

The relative bond slip was measured at the unloading side of the concrete prism by using a dial gauge until the point of general bond slip (Figures 3.19 and 3.20). The dial gauge had an accuracy of 1/10,000".

3.6 Test Procedure

The general procedure is as follows:

1. Clean up the test frame and oil the surface of the third fixed plate by using a piece of cloth (Figure 3.19).

2. Apply 300 to 500 pounds of pressure to install the load cells and loading instrument assembly. Steel is installed without eccentricity and without touching the hole at the load cell and fixed plates. This steel placement is checked precisely so that it does not touch the side of the four fixed plate holes (Figures 3.1 and 3.7). Because only a small load is applied, steel is easily moved to the position required (Figure 3.2).

3. Steel is stressed up to 50% to 55% of the guaranteed ultimate tensile strength of the strand. Two load cells are

Figure 3.17 View of Handpump.

Figure 3.18 View of Needle Valves.

Figure 3.19 View of Dial Gauge and Mount with Third Fixed Plate (I).

Figure 3.20 View of Dial Gauge and Mount (II).

installed to measure equal forces at each side of the concrete block during the loading to check the steel placement. Steel placement is adequate when the two load cells have the same difference in output value. The procedure for anchorage shimming to minimize seating loss during the concrete hardening is considered. The anchorage shimming procedure is as follows:

a) 21 to 24 Kips is applied to the strand, the second chuck is moved to the second fixed plate, and then the tension is released to 5 Kips (Figure 3.2 b).

b) The strand is stressed again until at 21 to 24 kips; shims with variable thickness are inserted into the gap between the chuck and the second fixed plate (Figure 3.7).

c) This procedure is repeated to achieve the required tensioning after release. Generally, three to four shims of variable thickness are installed.

4. Forms are installed and concrete is cast. Compacting of the concrete is performed by external vibration of the forms and striking 10 times on each side of the steel. Three cylinders are prepared by the same procedure (Figure 3.5).

5. The modified Gillmore test is performed on the concrete prism to check the setting of the cement before steam curing.

6. After satisfying the modified Gillmore test, the prism and cylinders are steam cured under the same conditions (Figures 3.10 and 3.11).

7. The forms are removed. A dial gauge is installed and a plastic cell is attached on the concrete surface by gluing to measure the slip (Figures 3.19 and 3.20).

8. The specimen is cooled to normal temperature. A compression test is performed on all three cylinders (Figure 3.6).

9. The shims in the second chuck are removed by applying a minimum additional force (generally 21 to 24 Kips) to the first chuck. The additional force is generally 2 to 4 Kips.

10. Loading is reduced (by 200 pounds bare and by 300 pounds coated) at the unloading side by opening a valve. This continues until general bond slip occurs. The first needle valve is opened a small amount to control the speed of unloading, and the unloading amount is controlled by the second valve (Figure 3.18). Generally, 10 to 15 seconds are needed to reduce the load by 200 or 300 pounds from the unloading side.

11. Maximum bond stress is defined by observing an abrupt general bond slip, which is greater than 0.01" in slip. After general slip occurs, the bond stress-slip is continuously measured to observe bond behavior after failure.

CHAPTER 4

ANALYTICAL MODEL

4.1 Introduction

In this chapter, a new analytical approach is considered in order to better understand the transfer bond mechanism in the anchorage zone of a prestressed, pretensioned concrete beam. The transfer length is divided into an elastic and a plastic zone. It is assumed that the bond stress increases proportionally with the slip to the limit of plastic maximum bond stress within the elastic zone and remains at a constant maximum value within the plastic zone. The maximum bond stress and bond stress-slip relationships are obtained from the regression analysis on the results of the suggested test in Chapter 3 with similar bond conditions within the transfer length during the transfer of prestressing force.

The bond stress and slip developed from the end of the transfer length at zero condition; thus, it is reasonable to define the elastic zone first. The remaining plastic zone can be determined from the equilibrium condition between the steel and maximum bond stresses from the end of the elastic zone. The proposed anchorage transfer bond mechanism is based on

four main variables. These are; bond slip, bond stress, steel stress, and concrete stress distribution along the longitudinal axis within the transfer length.

4.2 Stress Analysis Within the Elastic Zone

It is assumed that the slip and the three stresses of interest are interrelated within the elastic zone. The point where bond stress and slip are zero, as shown in Figure 2.3, is considered as the origin of the coordinate system. The following four relations are used to solve for these unknowns (Figure 4.1):

1. The equilibrium condition between bond and decreased steel forces is given as follows (Figure 4.1-a).

$$F_{sx} = f_{se} - \frac{\phi}{A_{ps}} \int_0^x T_x \, dx \tag{4.1}$$

Evaluating the derivative of Equation (4.1), we get Equation (4.2).

$$d(F_{sx}) = - T_x \frac{\phi \, dx}{A_{ps}} \tag{4.2}$$

2. The equilibrium condition between steel and concrete forces is as follows.

$$F_{cx} = - F_{sx} \frac{A_{ps}}{A_c} \tag{4.3}$$

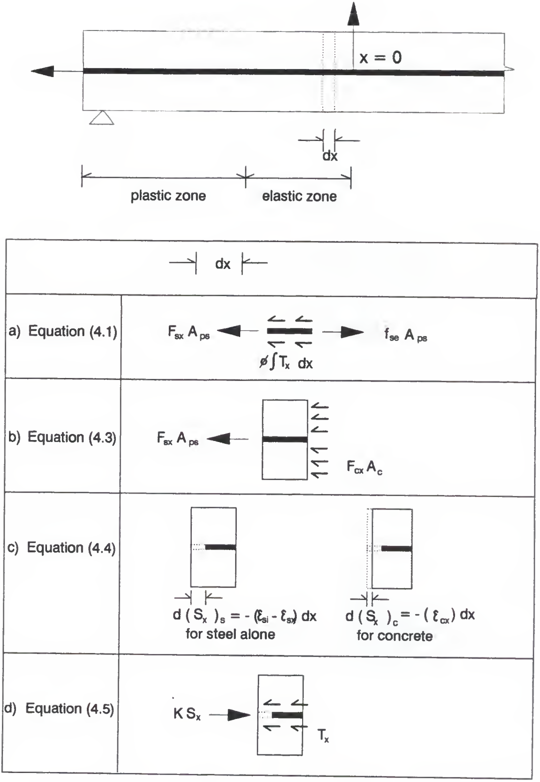


Figure 4.1 Typical Relation between Bond-Slip; Steel, Bond, and Concrete Stress.

3. The compatibility condition of relative displacement between concrete and steel due to the shortening of the strand from its initial steel stress to a steel stress after loss and an elastic shortening of concrete in the length, dx, is as follows

$$\frac{d(S_x)}{dx} = (-\varepsilon_{si} + \varepsilon_{sx}) - \varepsilon_{cx} = -\frac{f_{si}}{E_{ps}} + \frac{F_{sx}}{E_{ps}} - \frac{F_{cx}}{E_c} \tag{4.4}$$

4. The assumed bond stress-slip relation within the elastic zone for small displacements of the strand relative to the concrete is

$$T_x = -K\,S_x < T_{\max} \tag{4.5}$$

In Equation (4.5), the bond stress-slip relationships are assumed as linear elastic. The test results in Chapter 3 indicate that this relationship could vary within 10 Ksi. As an example, in the bond stress-slip curve shown in Figure 4.2 for specimen CS-5 with a grit-impregnated, epoxy-coated strand, the bond stress-slip relation can be selected with either K of 98.2 or K of 105.0 K/in^3. Increasing or decreasing the K-values within 10 K/in^3 does not alter the theoretical length of the elastic zone considerably. The proposed Equation (4.5) assumes that the relationship between bond stress and slip increases is linear elastic until there is maximum bond stress, $T_{\max}$; this is assumed by Guyon [7] (p.

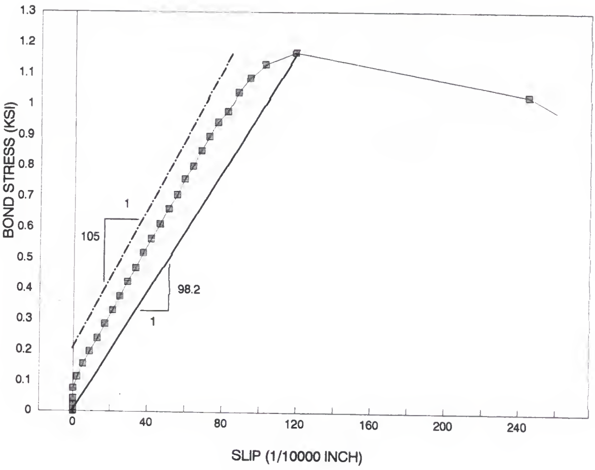


Figure 4.2 Example of Bond Stress-Slip Relationship.

188) and Cousins et al. [17] (p. 94) in their analytical studies. The bond stiffness, K, is influenced by concrete strength and estimated by the use of Equation 4.6 from a regression analysis of the test results in Chapter 5.

$$K = U'_k \sqrt{f'_{ci}}$$
$$f'_{ci} = initial\ concrete\ strength\ in\ psi \tag{4.6}$$

Table 4.1 Results of Regression Analysis from Tests in Chapter 3 for Bond Stiffness, K.

Specimen	U'_k(psi)
1/2" Coated Strands	1424
1/2" Bare Strands	1779

Note: refer to regression analysis in Chapter 5.

By substituting Equation (4.3) into Equation (4.4), we get

$$\frac{dS_x}{dx} = -\frac{f_{si}}{E_{ps}} + M\,A_{ps}\,F_{sx} \tag{4.7}$$

where M is

$$M = \frac{1}{E_{ps}\,A_{ps}} + \frac{1}{E_c\,A_c} \tag{4.8}$$

By substituting Equations (4.2) and (4.5) into Equation (4.7), the following second-order differential equation can

be defined in terms of bond slip to satisfy Equations (4.2), (4.3), (4.4), and (4.5) within the elastic zone.

$$\frac{d^2(S_x)}{dx^2} - K_1^2 \, S_x = 0 \tag{4.9}$$

where K_1 is

$$K_1 = \sqrt{K \, \Phi \, M} \tag{4.10}$$

The general solution of the second-order differential Equation (4.9) is

$$S_x = - A_1 \, Sinh(K_1 \, x) - B_1 \, Cosh(K_1 \, x) \tag{4.11}$$

Initial boundary conditions can be selected to solve for unknowns A_1 and B_1 in Equation (4.11) as follows:

1. The slip at the end of the transfer length is zero.

Boundary condition $S_x = 0$ at $x = 0$,

$$B_1 = 0 \tag{4.12}$$

The pull-in slip distribution within the elastic zone is

$$S_x = - A_1 \, Sinh(K_1 \, x) \tag{4.13}$$

2. The derivative of slip at the end of the elastic zone from Equations (4.7) and (4.13) is

$$\begin{aligned} \frac{dS_x}{dx} &= -\frac{f_{si}}{E_{ps}} + M\,A_{ps}\,f_{st} \quad at \;\; x = L_{te} \\ &= -A_1\,K_1\,Cosh(K_1\,L_{te}) \end{aligned} \tag{4.14}$$

The steel stress, f_{st}, at the end of the elastic zone can be obtained from the equilibrium condition between steel and bond stress in Equation (4.1).

$$\begin{aligned} f_{st} &= f_{se} - \frac{K\,\phi\,A_1}{A_{ps}} \int_0^{L_{te}} Sinh(K_1\,x)\;dx \\ &= f_{se} - \frac{K\,\phi\,A_1}{A_{ps}\,K_1}\left[Cosh(K_1\,L_{te}) - 1\right] \end{aligned} \tag{4.15}$$

By substituting Equation (4.15) into Equation (4.14), the unknown constant, A_1, is obtained,

$$A_1 = \frac{f_{si}}{E_{ps}\,K_1} - \frac{M\,A_{ps}\,f_{se}}{K_1} \tag{4.16}$$

The length of the elastic zone, L_{te}, can be found by trial and error.

$$0 = T_{max} - A_1\,K\,Sinh(K_1\,L_{te}) \tag{4.17}$$

The main stresses and slip patterns along the longitudinal axis within the elastic zone are given in the following sections.

4.2.1 Slip

The slip pattern within the elastic zone is given in Equations (4.13) and (4.16).

$$S_x = - A_1 \, Sinh(K_1 \, x) \qquad for \;\; 0 < x < L_{te} \qquad (4.18)$$

The slip due to steel stress alone is

$$S_{xs} = - A_{1s} \, Sinh(K_1 \, x) \qquad for \;\; 0 < x < L_{te} \qquad (4.19)$$

where A_{1s} is

$$A_{1s} = \frac{f_{si}}{E_{ps} \, K_1} - \frac{f_{se}}{K_1 \, E_{ps}} \qquad (4.20)$$

The decrease in total slip, S_x, due to concrete compressive stress is

$$S_{xc} = - A_{1c} \, Sinh(K_1 \, x) \qquad for \;\; 0 < x < L_{te} \qquad (4.21)$$

where A_{1c} is

$$A_{1c} = - \frac{A_{ps} \, f_{se}}{K_1 \, E_c \, A_c} \qquad (4.22)$$

4.2.2 Bond Stress

From the bond stress-slip relation in Equation (4.5), we get the following Equation (4.23) by multiplying -K in Equation (4.18),

$$T_x = A_2 \, Sinh(K_1 \, x) \qquad for \;\; 0 < x < L_{te} \qquad (4.23)$$

where A_2 is

$$A_2 = A_1 \, K \qquad (4.24)$$

4.2.3 Steel Stress

By substituting Equation (4.23) into Equation (4.1), we get

$$F_{sx} = f_{se} - A_3 \, \{Cosh(K_1 \, x) - 1\} \qquad for \; 0 < x < L_{te} \qquad (4.25)$$

where A_3 is

$$A_3 = (A_2 \, \phi) / (A_{ps} \, K_1) \qquad (4.26)$$

4.2.4 Concrete Compressive Stress

From the equilibrium conditions in Equation (4.3) between steel stress and concrete stress at the section considered, we can obtain the following formula for concrete compressive stress:

$$F_{cx} = -f_{se} \frac{A_{ps}}{A_c} + A_4 \{Cosh(K_1\, x) - 1\} \qquad for \;\; 0 < x < L_{te} \qquad (4.27)$$

where A_4 is

$$A_4 = A_3 \; (A_{ps}/A_c) \qquad (4.28)$$

4.3 Stress Analysis Within the Plastic Zone

The four main factors, the three stresses and slip, do not interact within the plastic zone. The maximum bond stress governs within the plastic zone. The steel stress and concrete stress will be decreased due to the maximum bond stress. The whole transfer length, stresses, and slip distribution are obtained by defining the location where steel stress is zero due to bond stress. The length of the plastic zone, L_{tp}, can be determined from the equilibrium between bond and steel stress.

$$L_{tp} = \frac{f_{st}\, A_{ps}}{T_{\max}\, \phi} \tag{4.29}$$

Now the transfer length, L_t, is

$$L_t = L_{te} + L_{tp} \tag{4.30}$$

Maximum bond stress and stiffness of the bond stress-slip relation are two of the most important factors in determining the bond stress and slip pattern. The results of the regression analysis for maximum bond stress are listed in Table 4.2 for bare and coated strands.

$$\begin{aligned} &T_{\max} = U'_t \sqrt{f'_{ci}} \\ &f'_{ci} = \textit{initial concrete strength in psi} \end{aligned} \tag{4.31}$$

Table 4.2 Results of Regression Analysis from Tests in Chapter 3 for Maximum Bond Stress.

Specimen	U'_t(psi)
1/2" Coated Strands	16.794
1/2" Bare Strands	6.185

Note: refer to regression analysis in Chapter 5.

4.3.1 Bond Stress

Bond stress remains at the maximum as shown in Equation (4.32).

$$T_x = T_{max} \qquad for \quad L_{te} \leq x < L_t \tag{4.32}$$

4.3.2 Steel Stress

The equilibrium condition between bond stress and steel stress is given as follows. From Equation (4.1), we get Equation (4.33),

$$F_{sx} = f_{st} - \frac{T_{max}\,\phi}{A_{ps}}\,(x-L_{te}) \qquad for \quad L_{te} \leq x < L_t \tag{4.33}$$

4.3.3 Concrete Compressive Stress

The first term of Equation (4.33), f_{st} is given in Equation (4.15). The concrete compressive stress is obtained by multiplying $- A_{ps}/A_c$ to Equation (4.33), and Equation (4.34) is obtained,

$$F_{cx} = -\,f_{st}\frac{A_{ps}}{A_c} + \frac{T_{max}\,\phi}{A_c}(x - L_{te}) \qquad for \quad L_{te} \leq x < L_t \tag{4.34}$$

4.3.4 Slip

By substituting $x = L_{te}$ in Equation (4.18) at the end point of the elastic zone, the first term of Equation (4.35) is obtained. The other terms of Equation (4.35) are obtained by evaluating the integral of Equation (4.7) and substituting F_{sx} in Equation (4.33).

$$S_x = - A_1 \, Sinh(K_1 \, L_{te}) - \frac{f_{si}}{E_{ps}} (x - L_{te}) + M \, A_{ps} \, f_{st} \, (x - L_{te}) - \frac{T_{max} \, \phi \, M}{2} (x^2 - 2 \, L_{te} \, x + L_{te}^2) \tag{4.35}$$

$$for \;\; L_{te} \le x < L_t$$

From Equation (4.35), the slip due steel stress alone,

$$S_{xs} = - A_{1s} \, Sinh(K_1 \, L_{te}) - \frac{f_{si}}{E_{ps}} (x - L_{te}) + \frac{f_{st}}{E_{ps}} (x - L_{te}) - \frac{T_{max} \, \phi}{2 \, E_{ps} \, A_{ps}} (x^2 - 2 \, L_{te} \, x + L_{te}^2) \tag{4.36}$$

$$for \;\; L_{te} \le x < L_t$$

From Equation (4.35), the decrease in total slip due to concrete compressive stress,

$$S_{xc} = - A_{1c} \, Sinh(K_1 \, L_{te}) + \frac{A_{ps} \, f_{st}}{E_c \, A_c} (x - L_{te}) - \frac{T_{max} \, \phi}{2 \, E_c \, A_c} (x^2 - 2 \, L_{te} \, x + L_{te}^2) \tag{4.37}$$

$$for \;\; L_{te} \le x < L_t$$

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

In this chapter, the results of the experimental test for bond properties from Chapter 3 and the results of the analytical work from Chapter 4 are considered. The experimental test results are based on the tests of two preliminary specimens of 1/2"-diameter bare strands without sufficient compaction on concrete, five specimens of 1/2"-diameter bare strands with sufficient compaction, and five specimens with grit-impregnated, epoxy-coated strands. The density of grit in epoxy-coating has not been considered individually as in the case of Cousins et al. [17,30,31,32]. The coated strands were handled in a careful manner; however, the coated strands were not separated into high, medium, and low density. The concrete compressive strength at the time of release was determined to evaluate its effect. The compressive strength was determined to range from 4 Ksi to 6 Ksi.

In Section 5.3, the analytical results are presented to find the effect of several variables on bond length and free-end slip. They are Young's modulus of steel, initial concrete

strength, bond stress-slip, concrete area, maximum bond stress over the square root of concrete strength, initial and effective steel stress, and the loss of steel stress after release. The results are also compared with ordinary transfer test results obtained by Cousins et al. [17,30,32].

5.2 Test Results

5.2.1 General

As mentioned previously in Chapter 3, 2 to 4 Kips was applied from the A side (Figure 3.1) to remove the second chuck by taking out the shims before the main test. This force increased the tensile steel stress and moved the concrete block from the oiled third fixed plate. After removing the second chuck, unloading was performed. The first several outputs on two load cells were lessened at the same rate until the concrete surface touched the oiled fixed plate. The difference between the two outputs was generally not zero even though the concrete block did not touch the third fixed plate (Figure 3.3 b and c). This may have resulted from the load cell calibration differences or load cell seating problems. However, it was not considered to be a problem because the same difference in outputs was noted in the loading procedure. Thus, the initial bond stress obtained

from the difference between these two load cells was considered zero by deducting this constant small difference (Figure 5.1). The constant difference started to change in lesser decrements at the fixed side load cell than at the unloading side load cell when the concrete block touched the third fixed face of steel as shown in Figure 5.1. The bond stress was increased in small amounts until the block settled down firmly (Figure 5.2).

After settling, the whole unloading force influenced the bond stress directly. As an example, the output on the unloading side of the load cell decreased by approximately 200 pounds for each 200 pounds unloading, but the other fixed side decreased by only 10 to 20 pounds due to slip (Figure 5.1). The first bond slip was recognized as approximately 0.000025" to 0.00005" when bond stress was around 150 psi in coated and 110 psi in uncoated strands (Figure 5.2). The bond stress and slip increased continuously by a small amount--from 0.0001" to 0.001" each for an unloading rate of 200 pounds for uncoated and 300 pounds for coated strands.

The slip of uncoated strands occurred and stopped at a certain value immediately after unloading. The coated strand slip moved continuously after unloading. A delay of 5 to 10 minutes was needed to achieve static equilibrium after unloading when the bond stress was high.

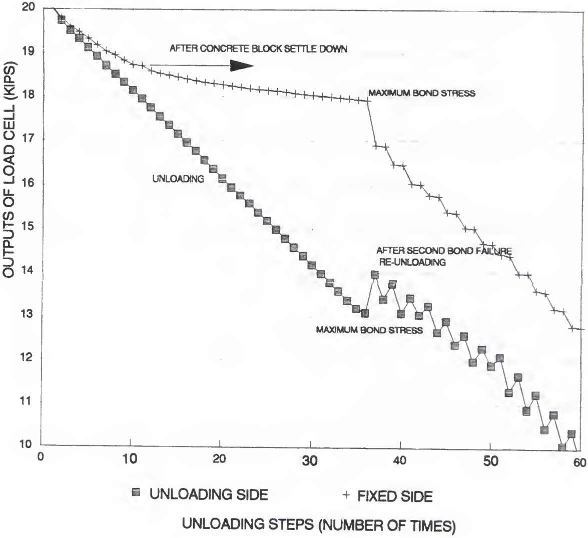


Figure 5.1 Typical Outputs of Two Load Cells (Model #US-5, Bare Strand).

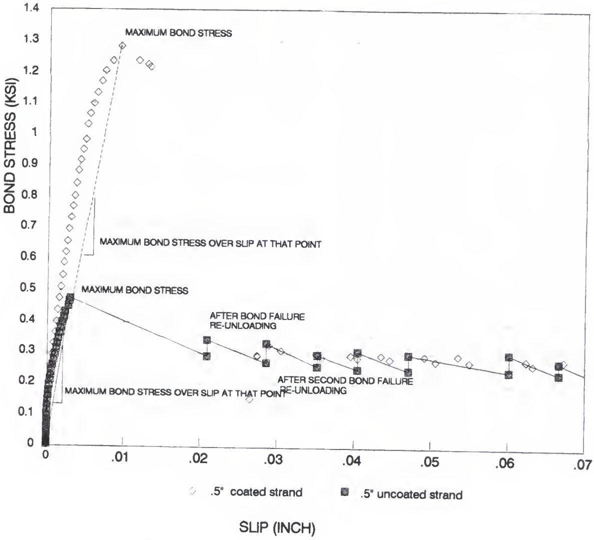


Figure 5.2 Comparison of Typical Bond Stress-Slip Relationships of Coated and Bare Strands (Model #US-5; Bare and #CS-1; Coated).

Maximum bond stress was attained at the point when the slip amount was abruptly increased to more than one-half round of the dial gauge needle at that point (generally 0.01"). When general bond slip occurred, the unloading side load cell increased in value and the other decreased due to the transfer in loading with a large slip (Figure 5.1); thus, the bonding force of the difference between these two load cells went down abruptly (Figure 5.2).

Another unloading test was performed after the first bond failure until a second bond failure resulted. The bond stress at a second failure was also recognized by observing the two outputs on the load cells. This difference was increased to a certain value and returned to the original condition after each failure (Figure 5.2). Generally, a 60- to 70-pound increase was observed after the failure for uncoated strands and a 10- to 15-pound increase for coated strands. This bond stress in Figure 5.2 did not decrease and was maintained at an average 270 psi in uncoated strands and 730 psi in coated strands even after 20 instances of continuous failure at a slip of 0.07", provided there was no splitting problem. This means that the frictional Hoyer effect bond stress cannot reach a null state due to slip within the transfer length, but remains at an almost constant value even after continuous failure.

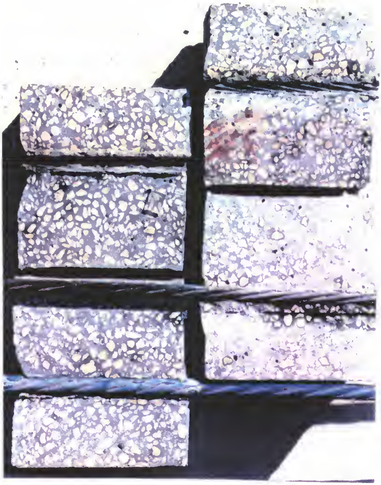


Figure 5.3 View of Strand Imprints Left in Concrete Blocks.

As pointed out by Dorsten et al. [12], the uncoated strand slips and rotates out of the concrete; thus, as shown in Figure 5.3, a smooth pattern was still left after the large 0.1" slip. In a coated strand case, some of the coating was removed, and the imprint shows no rotating of steel but only shear failure.

5.2.2 Uncoated Strand

The maximum bond stress with the Hoyer effect models are higher than those in the general pull-out test models because of the clamping action resulting from an increased steel cross section. The maximum bond stress in this test (Table 5.1) averages 464.08 psi for the bare strand. The maximum bond stress over the square root of concrete compression strength, U'_t, averages 6.18. This result is much greater than that of Brearly and Johnston's [28] pull-out test of 3.81. This value is also higher than that of 4.43 reported by the transfer tests with long specimens of Cousins et al. [17], but a little lesser than that of 7.0 reported by Cousins et al. [29] (Table 5.2). The slip at the point of maximum bond stress is 0.00353". The maximum bond stress over slip is averaged at 133.4 K/in^3.

The typical bond stress-slip is shown in Figures 5.4 to 5.8. These curves show that the bond slip starts at an average 110 psi, and the bond stress-slip relationship has a

Table 5.1 Summary of Test Results on 1/2"-Diameter Uncoated Strands: Specimens with Sufficient Compacting.

Sample	Test date	Strand diameter and surface condition	Dimension (in)
# US-1	8 - 13	1/2 inch, bare	6 x 6 x 6.203
# US-2	8 - 14	1/2 inch, bare	6 x 6 x 6.313
# US-3	8 - 18	1/2 inch, bare	6 x 6 x 6.078
# US-4	8 - 21	1/2 inch, bare	6 x 6 x 6.375
# US-5	8 - 27	1/2 inch, bare	6 x 6 x 6.500

Sample	T_{max} (psi)	Slip at T_{max} (in)	K T_{max}/Slip (K/in^3)	f'_{ci} (psi)	U'_t (psi)
# US-1	487.98	0.00378	129.3	5,914	6.35
# US-2	446.11	0.00398	112.2	5,472	6.03
# US-3	440.11	0.00367	119.9	5,201	6.10
# US-4	474.66	0.00323	147.2	6,024	6.12
# US-5	471.54	0.00298	158.5	5,573	6.32
Ave.	464.08	0.00353	133.4	5,637	6.18

Table 5.2 Comparison with Other Test Results on Average U'_t.

Type of Strand	(1) U'_t Brearly	(2) U'_t Cousins	(3) U'_t Cousins	U'_t This work
uncoated	3.67	7.00	4.43	6.18
coated	9.59	17.0	18.5	17.26

Source: (1) Pull-out test results from Brearly and Johnston [28],
(2) Results from Cousins, Badeaux and Mostafa [29],
(3) Transfer test results from Cousins, Johnston, and Zia [17,32].

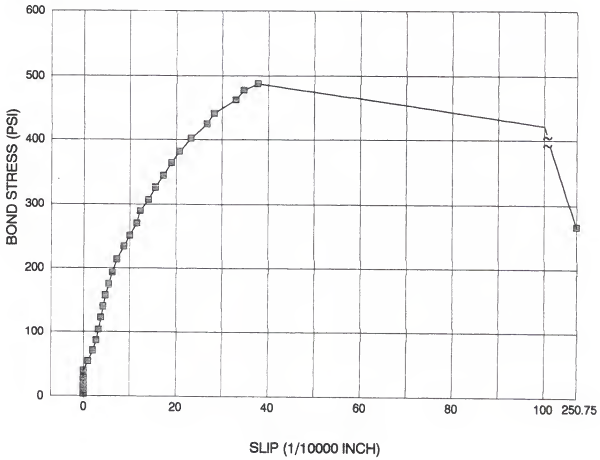


Figure 5.4 Bond Stress-Slip Relationship from Specimen #US-1 (1/2" Bare Strand).

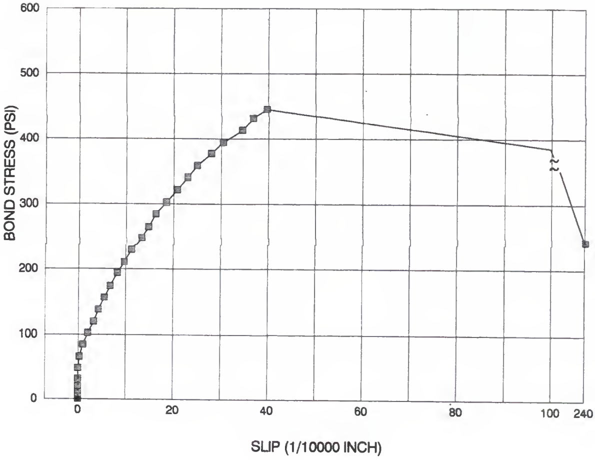


Figure 5.5 Bond Stress-Slip Relationship from Specimen #US-2 (1/2" Bare Strand).

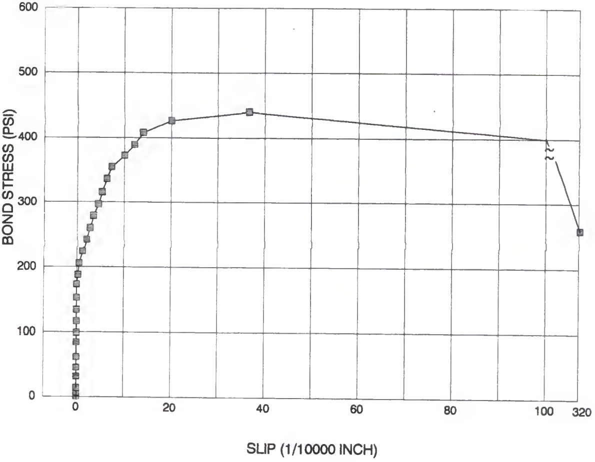


Figure 5.6 Bond Stress-Slip Relationship from Specimen #US-3 (1/2" Bare Strand).

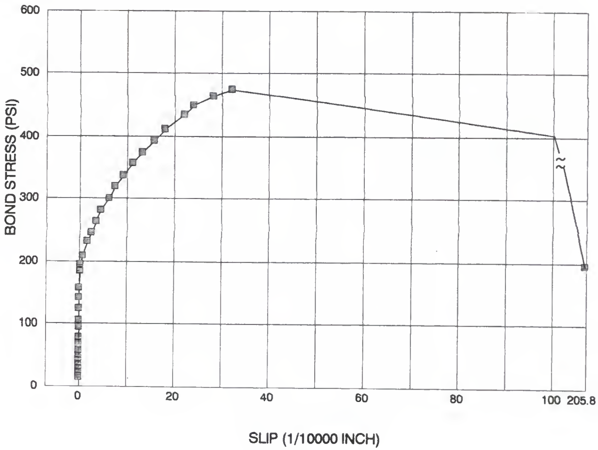


Figure 5.7 Bond Stress-Slip Relationship from Specimen #US-4 (1/2" Bare Strand).

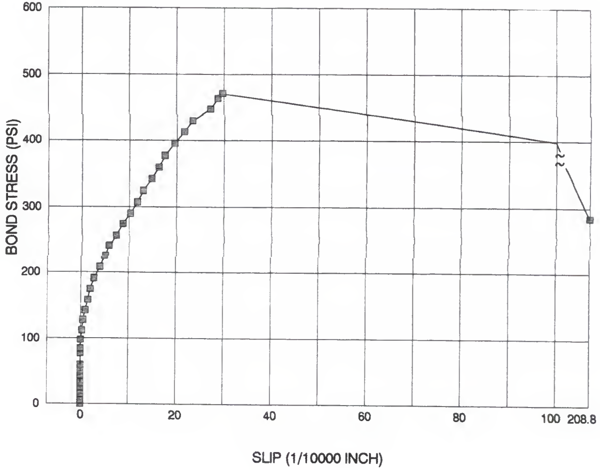


Figure 5.8 Bond Stress-Slip Relationship from Specimen #US-5 (1/2" Bare Strand).

higher value at its starting point but reduces as the bond stress increases at the same unloading rate. Bond stress goes down steeply after a maximum bond stress, implying abrupt bond failure in prestressed, pretensioned concrete beams (Figures 5.4 to 5.8).

5.2.3 Effect of Compacting on Concrete

One major problem encountered is that the maximum bond stress is considerably affected by compaction of the concrete. The vibration time on the forms and steel after casting the concrete is directly related to the compaction on the concrete. Specimens UC-1 and UC-2 in Table 5.3 show a small maximum bond stress (331.3 to 340.8 psi) due to less compaction of the concrete around the steel. The less compacted specimen was obtained by 10-second external vibration and without striking the steel directly, while the fully compacted specimen was obtained by vibration and striking the steel directly 10 times at both sides of the specimen after casting the concrete. The bond stress-slip curves for specimen UC-1 and UC-2 are similar in form, but differ in the maximum bond stress and stiffness, K, when comparing them with those of the US Series (Figures 5.9 and 5.10).

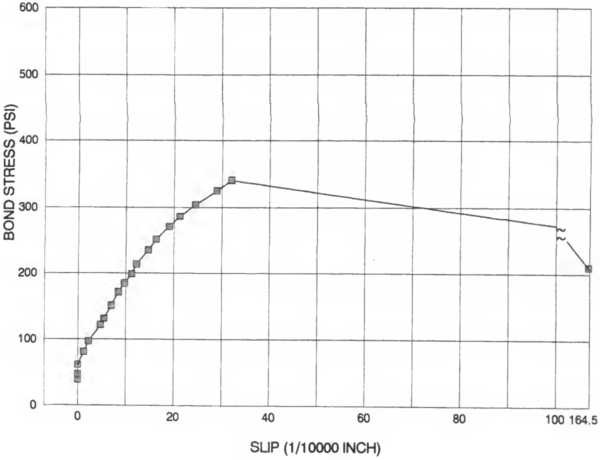


Figure 5.9 Bond Stress-Slip Relationship from Specimen #UC-1, W/O Full Compaction (1/2" Bare Strand).

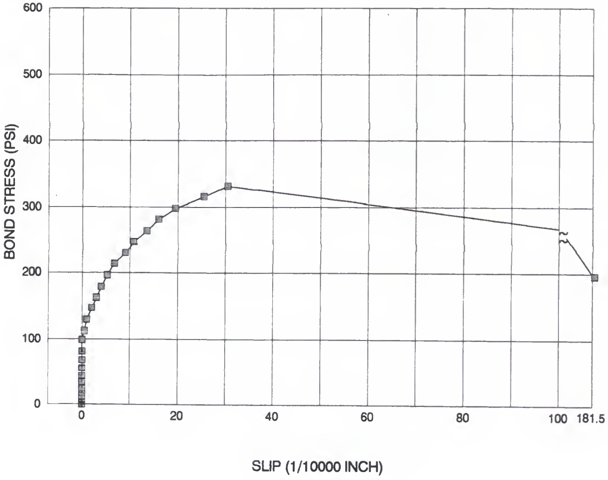


Figure 5.10 Bond Stress-Slip Relationship from Specimen #UC-2, W/O Full Compaction (1/2" Bare Strand).

Table 5.3 Summary of Test Results on 1/2"-Diameter Uncoated Strands: Specimens without Sufficient Compacting.

Sample	Testing date	Strand diameter and surface condition	Dimension (in)
# UC-1	8 - 12	1/2 inch - bare	6 x 6 x 6.22
# UC-2	8 - 26	1/2 inch - bare	6 x 6 x 6.44

Sample	T_{max} (psi)	Slip at T_{max} (in)	K T_{max}/Slip (K/in^3)	f'_{ci} (psi)	U'_t (psi)
# UC-1	340.8	0.00320	106.5	5,492	4.60
# UC-2	331.3	0.00305	108.6	5,010	4.68

5.2.4 Coated Strand

The same procedure used for uncoated strands is performed for coated strands except that a higher unloading rate, 300 lb, is used to save time. These specimens show a much larger maximum bond stress and slip amount than those of bare strands (Table 5.4). The thin samples (CS-1, CS-2) experienced minor splitting (cracking), but are included in averaging the results because they still have higher maximum bond stress comparable to those of samples without cracking (CS-3, CS-4, CS-5).

The maximum bond stress has an average of 1181.56 psi. The maximum bond stress over the square root of concrete strength, U'_t, averages 17.26 psi. This is much greater than that reported in pull-out tests by Brearly and Johnston [28] (12.35) and slightly greater than that of Cousins et al. [29] (17.0), but slightly less than that of transfer length tests

by Cousins et al. [17] (18.5) (Table 5.2). The average slip obtained at the point of maximum bond stress is 0.01196". It is interesting to note that the bond stiffness, K (maximum bond stress over slip at that point) averaged 99.5 K/in^3. This is a little less than that of the uncoated strand, 133.4 K/in^3.

Table 5.4 Summary of Test Results on 1/2"-Diameter Coated Strands.

Sample	Testing date	Strand diameter and surface condition	Dimension (in)
# CS-1	8 - 28	1/2 inch, coated	6 x 6 x 4.688
# CS-2	11 - 25	1/2 inch, coated	6 x 6 x 4.100
# CS-3	12 - 2	1/2 inch, coated	6 x 6 x 7.200
# CS-4	12 - 5	1/2 inch, coated	6 x 6 x 6.100
# CS-5	12 - 9	1/2 inch, coated	6 x 6 x 6.000

Sample	T_{max} (psi)	Slip at T_{max} (in)	T_{max}/Slip (K/in^3)	f'_{ci} (psi)	U'_t (psi)
# CS-1	1281.6	0.00931	137.7	5,458	17.35*
# CS-2	1203.2	0.01327	90.7	5,852	15.72*
# CS-3	1176.6	0.01433	75.3	3,325	18.70
# CS-4	1168.0	0.01230	95.7	5,227	16.27
# CS-5	1181.6	0.01190	98.2	4,887	16.71
Average	1181.6	.01196	99.5	4,724	17.26

Note: *minor cracking - CS-1, CS-2.

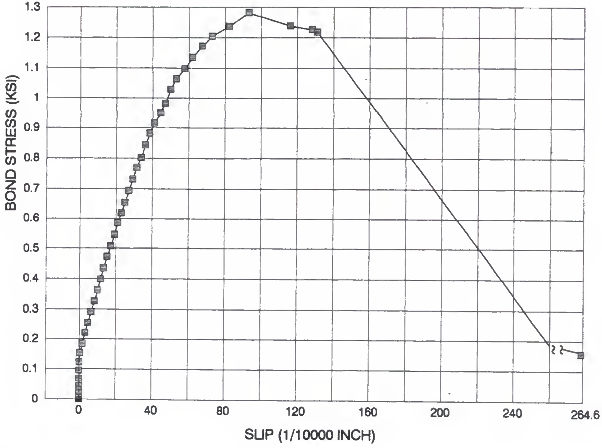


Figure 5.11 Bond Stress-Slip Relationship from Specimen #CS-1 (1/2" Coated Strand).

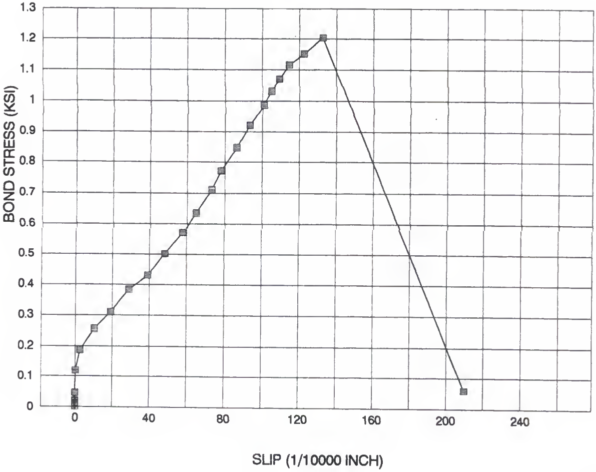


Figure 5.12 Bond Stress-Slip Relationship from Specimen #CS-2 (1/2" Coated Strand).

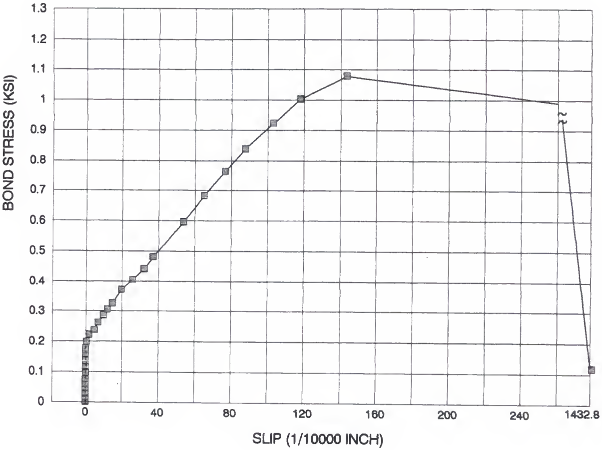


Figure 5.13 Bond Stress-Slip Relationship from Specimen #CS-3 (1/2" Coated Strand).

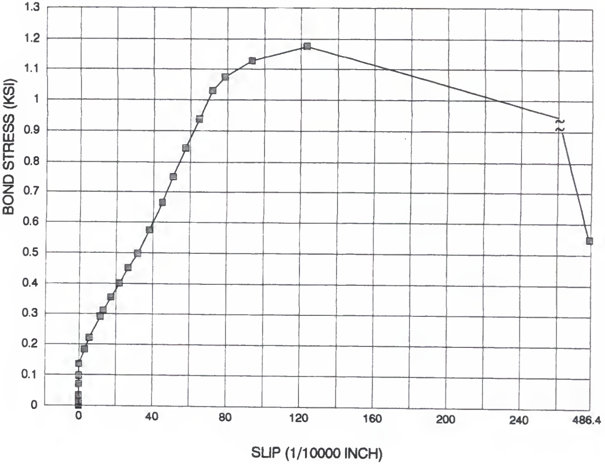


Figure 5.14 Bond Stress-Slip Relationship from Specimen #CS-4 (1/2" Coated Strand).

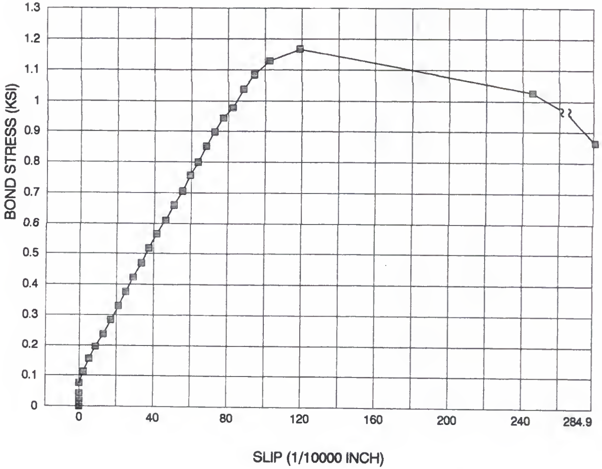


Figure 5.15 Bond Stress-Slip Relationship from Specimen #CS-5 (1/2" Coated Strand).

The bond stress-slip curve, as shown in Figures 5.11 to 5.15, exhibits a pattern similar to that of an uncoated strand, differing only in the maximum value and bond stiffness. This bond stress also goes down more sharply than in the case of an uncoated strand. The specimens with a minor splitting problem experienced more abrupt, greater slip, and less bond stress remained after failure.

5.2.5 Regression Analysis for Maximum Bond Stress

According to Kaar et al. [14], the frictional bond stress with the Hoyer effect has no relationship to concrete strength. Javor and Lazar [5] mentioned that concrete strength is not important, but density and consistency are the main factors for bond stress in seven-wire strands.

Deatherage and Burdette [11] concluded that the transfer length decreases slightly with increasing concrete strength. Cousins et al. [17,32] compared their results with those of other studies on the basis of U'_t, which is the maximum bond stress over the square root of concrete strength. However, there has not been any reasonable study done on the degree of concrete strength effect on the maximum bond stress of seven-wire prestressing strands within the transfer length.

Careful consideration is given to vibration time and curing on the five bare-strand and coated specimens. The maximum bond stress and stiffness, K, are analyzed by using

linear regression analysis according to the initial concrete strength $(f'_{ci})^{1/2}$ for the bare and coated strands. The statistical package program, SAS (Statistical Analysis System), is used for the t-test of the suggested model. Montgomery and Peck [43] mentioned, "A no-intercept model often seems appropriate in analyzing data from chemical and other manufacturing processes" (p. 38). Generally it is found that the t-statistic for testing H_0: $\beta_o = 0$ is not significant when using the intercept model (Tables 5.5 and 5.6). The no-intercept model provides a fit superior to those for the intercept model (Tables 5.7 and 5.8).

Table 5.5 Estimation of Maximum Bond Stress for Bare Strands--Intercept Model.

Vari-able	DF	Parameter Estimate	Standard Error	T for H_0: Parameter	R-square	Prob > T
β_o	1	-131.41	189.81	-0.69	0.7665	0.5385
β_1	1	7.93	2.53	3.14		0.0517

Table 5.6 Estimation of Maximum Bond Stress for Coated Strands--Intercept Model.

Vari-able	DF	Parameter Estimate	Standard Error	T for H_0: Parameter	R-square	Prob > T
β_o	1	597.31	221.52	2.70	0.7005	0.0740
β_1	1	8.34	3.15	2.65		0.0771

Table 5.7 Estimation of Maximum Bond Stress for Bare Strands--No-intercept Model.

Vari-able	DF	Parameter Estimate	Standard Error	T for H_0: Parameter	R-square	Prob > T
β_1	1	6.184677	0.062691	98.654	0.9996	0.0001

Table 5.8 Estimation of Maximum Bond Stress for Coated Strands--No-intercept Model.

Vari-able	DF	Parameter Estimate	Standard Error	T for H_0: Parameter	R-square	Prob > T
β_1	1	16.793652	0.469983	35.733	0.9969	0.0001

From Table 5.7, it appears that the $(f'_{ci})^{1/2}$ is a useful predictor of T_{max} in the no-intercept model, $T_{max}=\beta_1 \times (f'_{ci})^{1/2}$. The p-value for slope is less than 0.05; thus, it is confident that there is a linear relationship between T_{max} and $(f'_{ci})^{1/2}$. The true value, β_1 lies between 6.12 and 6.25. The analytical prediction in Equation 5.1 for maximum bond stress of bare strands is obtained precisely. In Figure 5.16, the result of Equation 5.1 is shown with the test results of bare strands for T_{max} and $(f'_{ci})^{1/2}$.

$$T_{max} = 6.18 \sqrt{f'_{ci}} \tag{5.1}$$

From Table 5.8, the $(f'_{ci})^{1/2}$ is still a useful predictor of T_{max} in the regression model. The p-values for the slope, β_1, are 0.0001, less than assumed type I error-0.05; thus, it is evident that there is a linear relationship between T_{max} and $(f'_{ci})^{1/2}$. The true value of β_1 lies between 16.32 and 17.26. The analytical prediction for maximum bond stress for coated strands is given by Equation 5.2. In Figure 5.17, the results from Equation 5.2 are shown for coated strands.

$$T_{max} = 16.80 \sqrt{f'_{ci}} \tag{5.2}$$

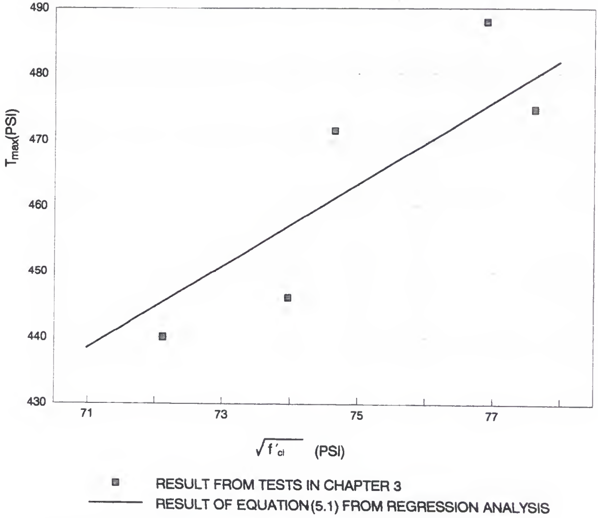


Figure 5.16 Regression Analysis for Maximum Bond Stress (1/2" Bare Strand).

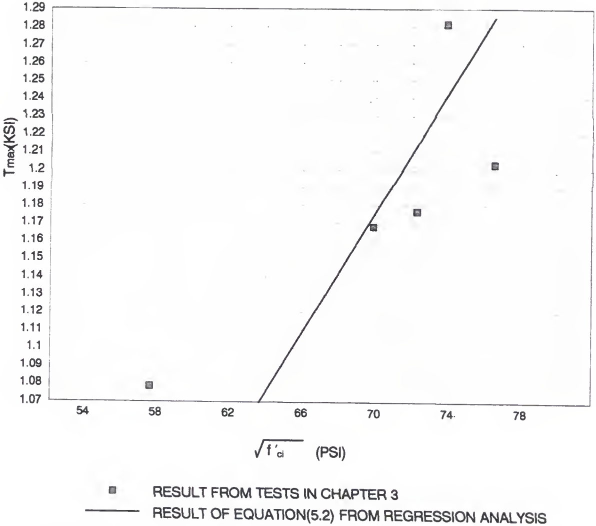


Figure 5.17 Regression Analysis for Maximum Bond Stress (1/2" Coated Strand).

5.2.6 Regression Analysis for Bond Stress-Slip Relationship

The t-test is also conducted for the relationship between concrete cube strength and bond stiffness, K, for bare and coated strands. From Tables 5.9 and 5.10, the concrete strength in terms of $(f'_{ci})^{1/2}$ is still significant for the stiffness, K-value. The regression analysis for bond stiffness is shown in Figure 5.18 for bare strands and in Figure 5.19 for coated strands. This expression for bare strands is as follows:

$$K = 1.78 \sqrt{f'_{ci}} \tag{5.3}$$

and for coated strands,

$$K = 1.42 \sqrt{f'_{ci}} \tag{5.4}$$

Table 5.9 Estimation of Bond Stress-Slip Relationships for Bare Strands.

Variable	DF	Parameter Estimate	Standard Error	T for H_0: Parameter	R-square	Prob > T
β_1	1	1.779289	0.105155	16.921	0.9862	0.0001

Table 5.10 Estimation of Bond Stress-Slip Relationships for Coated Strands.

Variable	DF	Parameter Estimate	Standard Error	T for H_0: Parameter	R-square	Prob > T
β_1	1	1.423785	0.122656	11.608	0.9712	0.0003

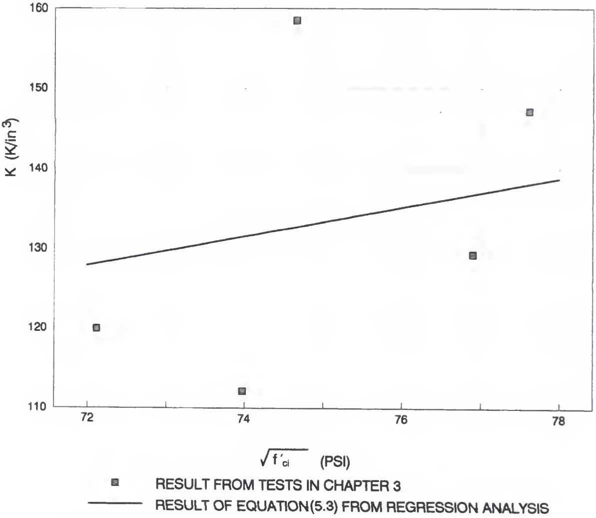


Figure 5.18 Regression Analysis for Bond Stress-Slip Relationship (1/2" Bare Strand).

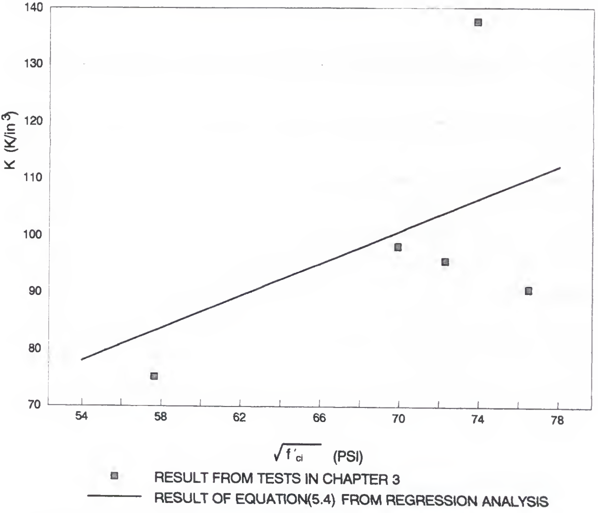


Figure 5.19 Regression Analysis for Bond Stress-Slip Relationship (1/2" Coated Strand).

5.2.7 Regression Analysis for Rusting Effect

It has been confirmed that the transfer length of a bare strand is also affected by the rusting phenomenon from the date of manufacturing to the date of casting the concrete. However, several tests were conducted over a period of two weeks and did not show any increase in maximum bond stress due to rust on the surface of the steel within a duration of two weeks under laboratory conditions (refer to Table 5.1). Regression analysis was also conducted for the relationships between the U'_t value and the number of days after receiving. As shown in Table 5.11, the p-value is 0.68, much higher than 0.05 (whereas R-square is 0.0640). It seems that no relationship is defined because the p-value is much higher than the type I error for the slope, β_1. Thus, rust is not a major influencing factor for bond stress within a duration of two weeks under laboratory conditions. However, the compaction of concrete surrounding the steel and the concrete cube strength are major influences.

Table 5.11 Estimation of Rusting Effect.

Variable	DF	Parameter Estimate	Standard Error	T for H_0: Parameter	R-square	Prob > T
β_0	1	6.142	0.1164	52.744	0.0640	0.0001
β_1	1	0.006	0.0140	0.453		0.6814

5.3 Analytical Results

5.3.1 General

In their experimental work, Cousins et al. [17,30,32] made great progress in the study of transfer bond length of a prestressed concrete beam. Use of a two-inch interval strain gauge on a concentrated single strand specimen gives a reasonable result within the transfer length. This test result is selected for comparison with the proposed analytical work for the following reasons: 1) elastic and plastic zones and free-end slip are observed; 2) a relatively short, two-inch, interval strain gauge placement is adopted; and 3) a single strand in the reduced section is measured for bond stress.

Input data for the analytical study, as shown in Table 5.12, are obtained from the experimental data of Cousins et al. [17,32]. Eccentric members, for instance, the specimen S series, may be subject to a bending and torsion effect. The 1.25" eccentric samples, S series, may have slightly less maximum bond stress than that of concentric samples under the same conditions, but are still considered because they use more concrete area, 40 in^2. On the other hand, the concentric sample, T series, has only 16 in^2 in concrete area. Low-coated specimens are not included because they are not considered in the tests listed in Chapter 3.

Table 5.12 Input Data Obtained from Previous Transfer Test Data.

Specimen (No. of tests)	E_{ps} (Ksi)	A_c (in²)	A_{ps} (in²)	f'_{ci} (Ksi)	f_{si} (Ksi)	f_{se} (Ksi)
T5una-d(4) G	28,400	4 x 4	0.153	4.11	208.3	181.1
T5une-h(4) S	28,400	4 x 4	0.153	4.11	204.6	179.7
S5una-b(2) S	28,400	5 x 8	0.153	4.06	210.2	200.7
S5unc-h(6) S	28,400	5 x 8	0.153	4.41	210.5	199.1
S5uni-j(2) S	28,400	5 x 8	0.153	4.81	204.6	194.7

Specimen (No. of tests)	E_{ps} (Ksi)	A_c (in²)	A_{ps} (in²)	f'_{ci} (Ksi)	f_{si} (Ksi)	f_{se} (Ksi)
T5cma-b(2) G	28,400	4 x 4	0.153	4.11	208.3	179.1
T5cha-d(4) G	28,400	4 x 4	0.153	4.11	196.8	176.3
S5cma-b(2) S	28,400	5 x 8	0.153	4.06	212.9	202.5
S5cmc-f(4) S	28,400	5 x 8	0.153	4.41	208.0	196.3
S5cmg-j(4) S	28,400	5 x 8	0.153	6.72	208.2	198.5
S5cha-d(4) S	28,400	5 x 8	0.153	3.89	207.8	196.2

Source: Cousins et al. [17,32].

Note: T5un - 1/2" diameter, concentrated, and uncoated specimens,
T5cm - 1/2" diameter, concentrated, and medium coated specimens,
T5ch - 1/2" diameter, concentrated, and high coated specimens,
S5un - 1/2" diameter, eccentric (1.25"), and uncoated specimens,
S5cm - 1/2" diameter, eccentric (1.25"), and medium coated specimens,
S5ch - 1/2" diameter, eccentric (1.25"), and high coated specimens,
S - sudden release specimens,
G - gradual release specimens.

The coated strand is a little larger in diameter than the bare strand. However, from the test results in Tables 5.1 and 5.4, the maximum bond stress and its relationship with slip are calculated on the basis of a strand 1/2" in diameter; thus, this same value is used for the analysis. The actual perimeter of the bare strand is ($4/3\ d_b\ \pi$). It is calculated based on $d_b\ \pi$ because this value was used in the test data listed in Chapter 3. The use of $d_b\ \pi$ is to avoid confusion when comparing those results with other studies.

5.3.2 Elastic Zone

The average length of the elastic zone in Table 5.13 is determined to be 6.05" for specimens of concentric 1/2" bare strands in small concrete sections (12.7% of total calculated transfer length), and 10.05" for eccentric 1/2" bare strands in larger concrete sections (19.8%) (Figure 5.20). The case of the coated strand specimen averages 13.1" for specimens of concentric strands (52.7% for total transfer length), and 16.8" for eccentric strands under the same conditions as above (58.3%). This length for specimens of concentric 1/2" bare strands in small concrete sections (12.7%) is comparable to the 13% estimated by Cousins et al. [17]. However, the elastic zones are generally much larger than the value of 13% as assumed by Cousins et al. [17] in their analytical study.

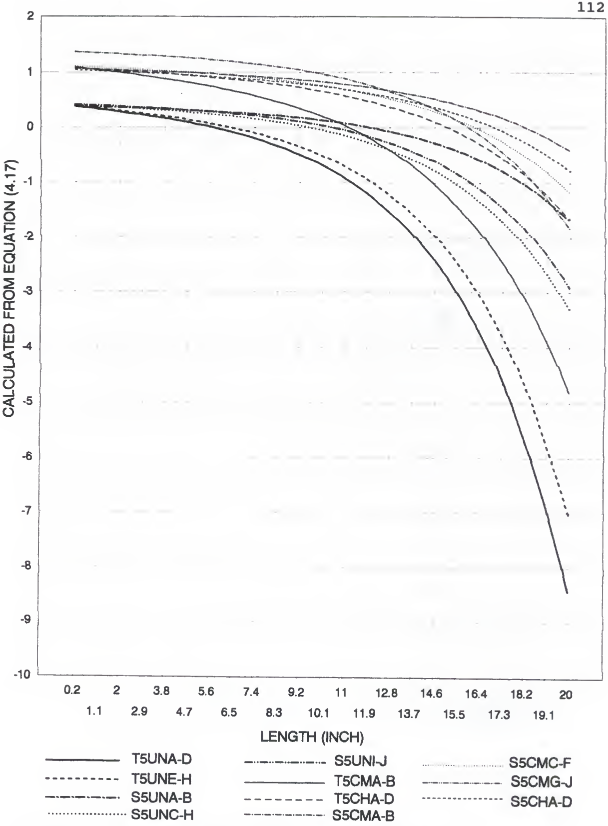


Figure 5.20 Analytical Prediction for Elastic Zone within Transfer Length.

The main reason for the large difference in the elastic zone between eccentric and concentric strands is amount of initial and effective steel stress (Table 5.12).

Table 5.13 Comparison with Transfer Test Data by Cousins et al.

Specimen (No. of tests)	1 day, measured L_t by Cousins et al. (in)	(1) L_{te} Calc. (in)	(2) L_{tp} Calc. (in)	(1)+(2) L_t Calc. (in)
T5una-d (3) G	N/A	5.70	41.97	47.67
T5une-h (3) S	62.5	6.40	41.40	47.80
S5una-b (2) S	48.0	11.95	45.55	57.50
S5unc-h (6) S	53.7	9.55	43.62	53.17
S5uni-j (2) S	45.0	10.45	40.48	50.93
Average measured/calculated				1.01
Standard deviation				0.21

Specimen (No. of tests)	1 day, measured L_t by Cousins et al. (in)	(1) L_{te} Calc. (in)	(2) L_{tp} Calc. (in)	(1)+(2) L_t Calc. (in)
T5cma-b (2) G	16.0	11.10	12.05	23.15
T5cha-d (4) G	16.1	15.10	11.21	26.31
S5cma-b (2) S	21.0	18.20	13.37	31.57
S5cmc-f (4) S	18.0	16.15	12.32	28.47
S5cmg-j (4) S	22.0	15.95	9.55	25.50
S5cha-d (4) S	18.5	16.95	13.22	30.17
Average measured/calculated				0.68
Standard deviation				0.09

5.3.3 Transfer Length and Slip

From the results shown in Table 5.14, it can be seen that the measured transfer bond length is comparable to the calculated length in bare strands. The measured length is much greater than calculated length in coated strands. The measured length is an average 101% of calculated length for a bare strand, and less than the calculated length, an average 68%, for a coated strand. This means that the maximum bond stress in a beam may be a little less in the case of the coated strands. However, the difference between the measured and predicted results for coated strand is consistent. The standard deviation is 0.09 for coated strands. On the other hand, results from ACI [1] (163%), and Zia and Mostafa [15] (180%) also show poor predictions for the bare, seven-wire prestressing strand (Table 5.14).

The pull-in slip at the free-end (Table 5.15) generally is comparable to that of measured value. The measured free-end slip is accurate up to an average of 115% of calculated free-end slip in a bare strand and 83% in a coated strand. However, this result shows consistent differences as standard deviations of 0.28 and 0.23 are achieved for an uncoated strand and a coated strand, respectively.

Table 5.14 Summary of Comparison on Calculated Transfer Length with Those of Other Equations.

Specimen (No. of tests)	(1) L_t Ave. Meas. (in)	(2) L_t Zia (in)	(3) L_t ACI (in)	(4) L_t Cousins (in)	Ave. L_t this work (in)
T5una-d (3) G	N/A	33.4	30.2	N/A	47.67
T5une-h (3) S	62.5	32.7	30.0	41.4	47.80
S5una-b (2) S	48.0	34.2	33.5	46.5	57.50
S5unc-h (6) S	53.7	31.2	33.2	44.3	53.17
S5uni-j (2) S	45.0	27.3	32.5	43.3	50.93
Average measured/calculated		1.80	1.63	1.20	1.01
Standard deviation					0.21

Specimen (No. of tests)	(1) L_t Ave. Meas. (in)	(2) L_t Zia (in)	(3) L_t ACI (in)	(4) L_t Cousins (in)	Ave. L_t this work (in)
T5cma-b (2) G	16.0	33.4	29.9	19.1	23.15
T5cha-d (4) G	16.1	31.3	29.4	18.0	26.31
S5cma-b (2) S	21.0	34.7	33.8	20.5	31.57
S5cmc-f (4) S	18.0	30.8	32.7	19.3	28.47
S5cmg-j (4) S	22.0	18.6	33.1	16.5	25.50
S5cha-d (4) S	18.5	35.5	32.7	20.3	30.17
Average measured/calculated		0.65	0.58	0.99	0.68
Standard deviation					0.09

Source: (1) experimental study by Cousins et al. [30,32],
(2) Zia and Mostafa [15],
(3) ACI provisions [1],
(4) analytical study by Cousins et al. [17].

Table 5.15 Comparison of Slip at Free-End with Test Results by Cousins et al.

Specimen (No. of tests)	1-day measured slip by Cousins (in)	Slip calculated in this study (in)
T5una-d (3) G	N/A	- 0.1758
T5une-h (3) S	- 0.252	- 0.1699
S5una-b (2) S	- 0.167	- 0.1885
S5unc-h (6) S	- 0.232	- 0.1816
S5uni-j (2) S	- 0.155	- 0.1647
Average measured/calculated		1.15
Standard deviation		0.28

Specimen (No. of tests)	1-day measured slip by Cousins (in)	Slip calculated in this study (in)
T5cma-b (2) G	- 0.046	- 0.0698
T5cha-d (4) G	- 0.044	- 0.0632
S5cma-b (2) S	N/A	- 0.0764
S5cmc-f (4) S	- 0.068	- 0.0705
S5cmg-j (4) S	- 0.069	- 0.0586
S5cha-d (4) S	- 0.050	- 0.0744
Average measured/calculated		0.83
Standard deviation		0.23

Source: Cousins et al. [17,32].

5.3.4 Stress and Slip Patterns

The elastic zone is estimated from Equation (4.17) in Chapter 4. The results for different input in Table 5.12 is shown in Figure 5.20. The bond, steel, and concrete stress and the slip patterns along the x axis are presented in Figures 5.21 to 5.24.

The final pull-in slip pattern is analyzed as the slip due to steel tensile strain minus the slip due to concrete compressive strain. As shown in Figure 5.25, the final slip pattern is determined precisely. Concrete, steel, and bond stress and the slip distribution exhibit similar patterns to those reported in recent work by Cousins et al. [17,32].

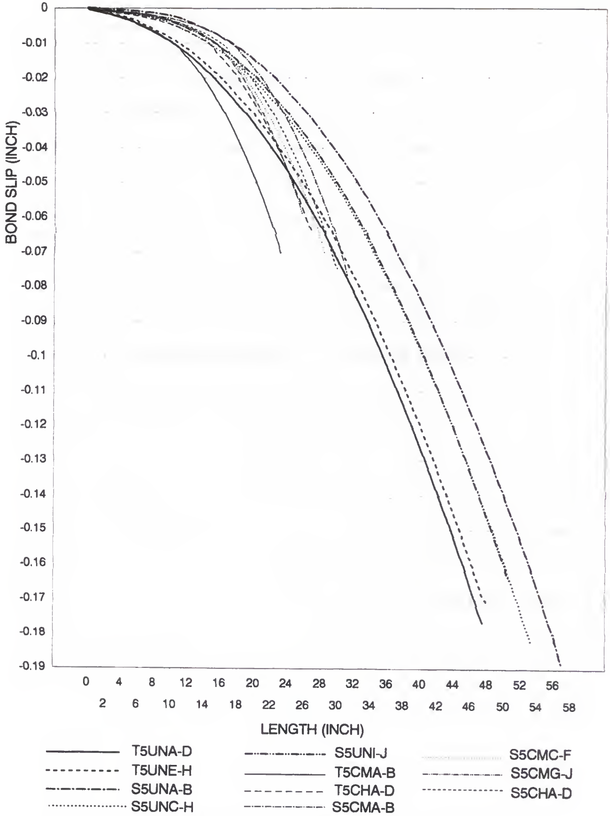


Figure 5.21 Analytical Prediction for Bond-Slip.

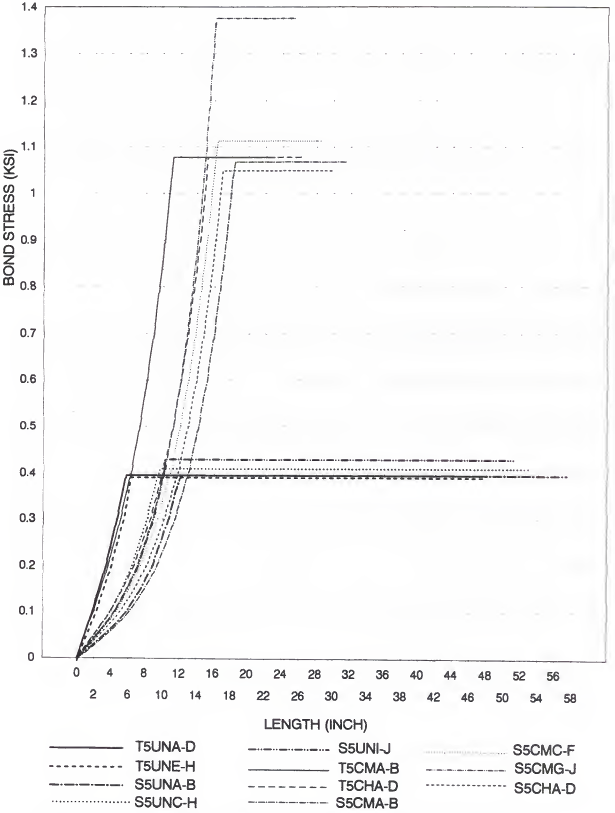


Figure 5.22 Analytical Prediction for Bond Stress.

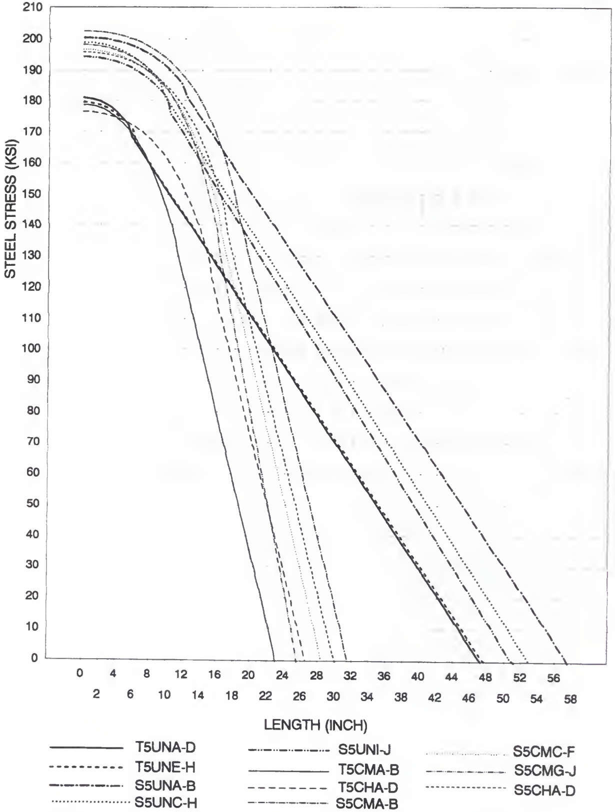


Figure 5.23 Analytical Prediction for Steel Stress.

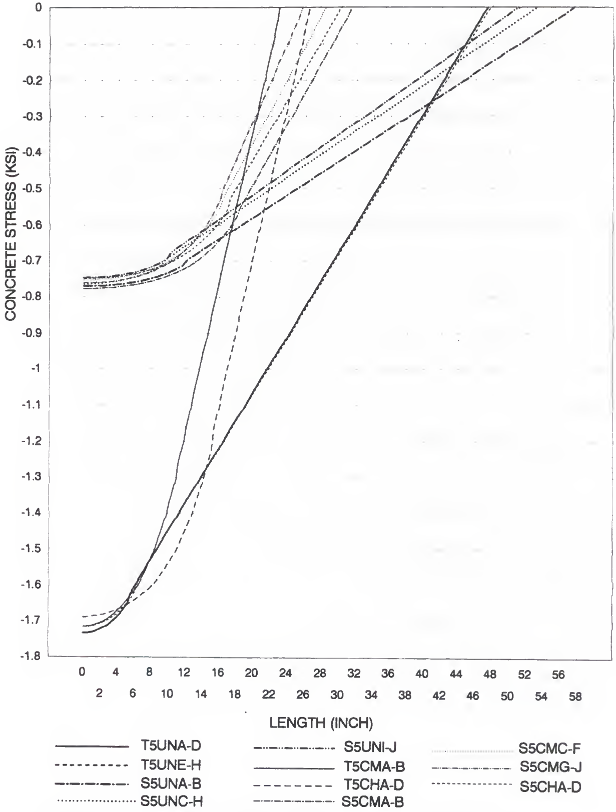


Figure 5.24 Analytical Prediction for Concrete Stress.

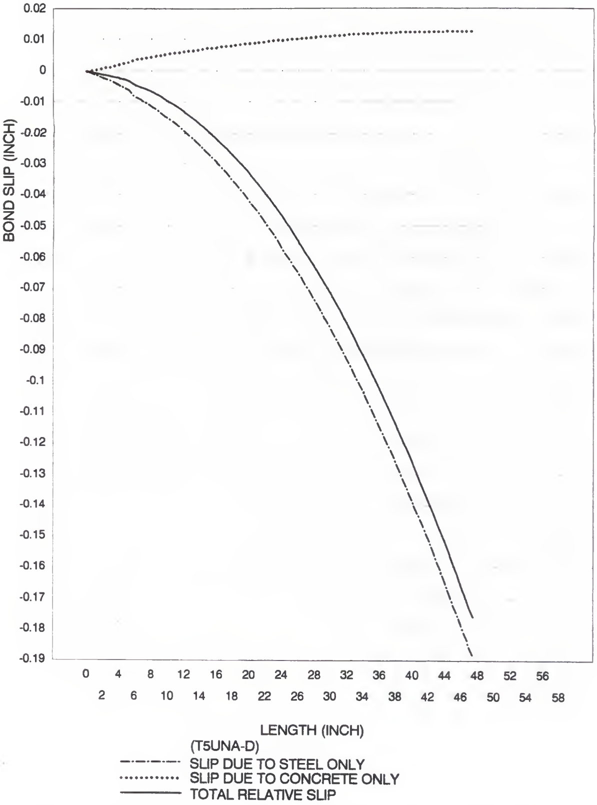


Figure 5.25 Typical Analytical Prediction for Bond-Slip Due to Steel and Concrete Strain Effect (Sample #T5UNA-D).

5.4 Effect of Various Variables on Bond

5.4.1 General

The transfer bond length and the slip at the free-end in pretensioned concrete beams are influenced by several variables. They are initial and effective steel stress, initial concrete strength, maximum bond stress, the bond stress-slip relationship, the modulus of steel, steel area, and concrete section area. The values of these parameters can be determined only experimentally. The effects of these variables have not been tested individually in previous studies, but it is apparent that a knowledge of the effect of each individual variable will help in understanding the bond characteristics within the transfer length and could save the cost of expensive experiments. Some of the variables mentioned above have been considered as minor in effect for evaluation of the transfer length. However, lack of information of several minor effects may eventually cause erroneous results.

The area of steel is not included because maximum bond stress and its relationship with slip were not tested for different sizes of strands in Chapter 3. Each effect of the main variable has been analyzed when others are fixed.

5.4.2 Initial Steel Stress and Loss

From Table 5.16, the effect of an increase in initial and effective steel stress is shown. It is assumed that initial and effective steel stresses increased together in the same amount, similar to the conditions as in the case of data compiled by Cousins et al. [17,32] in Table 5.12, while the initial concrete strength, concrete area, and bond stress-slip relationship have a constant value as listed in the note.

As shown in Figure 5.26, the increase of initial and effective steel stress from 160 and 150 Ksi to 210 and 200 Ksi produces an increase of the elastic zone, L_{te}, of 1.75" and an increase of the plastic zone of 4.1". The increase of the elastic and plastic zone produces an increase in total transfer bond length of 5.85". The pull-in bond slip also increases in free-end (Figure 5.26) of 0.0266". The increase of the initial jacking force is one of the most important factors in the increase of the transfer bond length and slip.

In Table 5.17, the initial steel stress increases from 180 Ksi to 230 Ksi while the effective steel stress remains at 170 Ksi. The increase in loss from the initial steel stress to the effective steel stress produces a decrease in the transfer length of more than 9.04". This result is mainly due to the large decrease in the elastic zone (11.15") and also to a small increase (2.11") in the plastic zone, as shown in

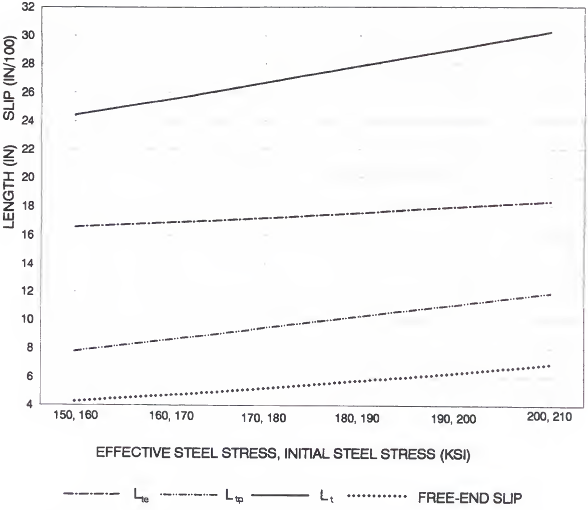


Figure 5.26 Analytical Prediction (1): Effect of Initial and Effective Steel Stress, f_{si} .

Figure 5.27. The large decrease in the elastic zone is from that the higher loss in steel stress produces the higher slip and bond stress in the section considered ($\varepsilon_{si}-\varepsilon_{se}$). The free-end slip shows an increase of 0.0201".

Table 5.16 Analytical Prediction (1) - Effect of Initial and Effective Steel Stress, f_{si}.

f_{si} (Ksi)	f_{se} (Ksi)	L_{te} (in)	L_{tp} (in)	L_t (in)	end slip (in)
160	150	16.60	7.81	24.41	-0.0427
170	160	16.90	8.63	25.53	-0.0474
180	170	17.20	9.48	26.68	-0.0525
190	180	17.55	10.29	27.84	-0.0578
200	190	17.95	11.09	29.04	-0.0634
210	200	18.35	11.91	30.26	-0.0693

Note: for coated strand when f'_{ci}=4.742 Ksi, E_{ps}=28,400 Ksi, A_c=36 in².

Table 5.17 Analytical Prediction (1) - Effect of Loss in Initial Steel Stress, $f_{si} - f_{se}$.

f_{si} (Ksi)	$f_{si} - f_{se}$ (Ksi)	L_{te} (in)	L_{tp} (in)	L_t (in)	end slip (in)
180	10	17.20	9.48	26.68	-0.0525
190	20	11.35	10.17	21.52	-0.0575
200	30	8.80	10.71	19.51	-0.0626
210	40	7.15	11.22	18.37	-0.0676
220	50	6.05	11.59	17.64	-0.0726

Note: for coated strand when f_{se}=170 Ksi, f'_{ci}=4.742 Ksi, E_{ps}=28,400 Ksi, A_c=36 in².

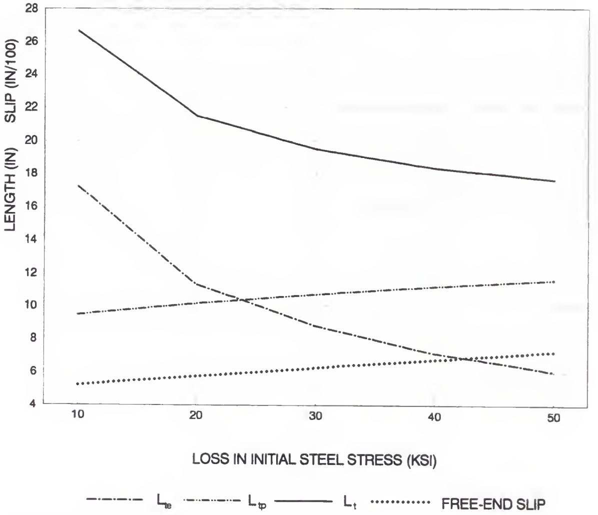


Figure 5.27 Analytical Prediction (1): Effect of Loss in Initial Steel Stress, $f_{si} - f_{se}$.

5.4.3 Maximum Bond Stress

The maximum bond capacity, U'_t, on specific types of steel is a result of size, type, and surface condition of the steel, internally, and the initial concrete strength, externally. The effect of internal (maximum bond stress) and external (concrete strength) factors is generally described in terms of U'_t in bond problems as mentioned in Chapters 2 and 4. An increase of U'_t by fixing the initial concrete strength will produce an increase in internal maximum bond stress (Table 5.18). As shown in Figure 5.28, this increase of maximum bond stress induces a decrease in plastic bond length of 19.38", but an increase in elastic bond length of 4.256" induces a decrease in total bond length of 15.13"; the slip at free-end also decreases by 0.0672".

Table 5.18 Analytical Prediction (2) - Effect of Maximum Bond Stress over the Square Root of Concrete Strength, U'_t.

U'_t (Ksi)	T_{max} (Ksi)	L_{te} (in)	L_{tp} (in)	L_t (in)	end slip (in)
8	0.5509	5.40	27.59	32.99	-0.1218
10	0.6886	6.35	21.22	27.57	-0.0987
12	0.8263	7.20	16.90	24.10	-0.0835
14	0.9641	7.90	13.84	21.74	-0.0729
16	1.1018	8.55	11.50	20.05	-0.0651
18	1.2395	9.10	9.70	18.80	-0.0592
20	1.3772	9.65	8.21	17.86	-0.0546

Note: for coated strand when f_{si}=200 Ksi, f_{se}=170 Ksi, E_{ps}=28,400 Ksi, A_c=36 in², f'_{ci}=4.742 Ksi.

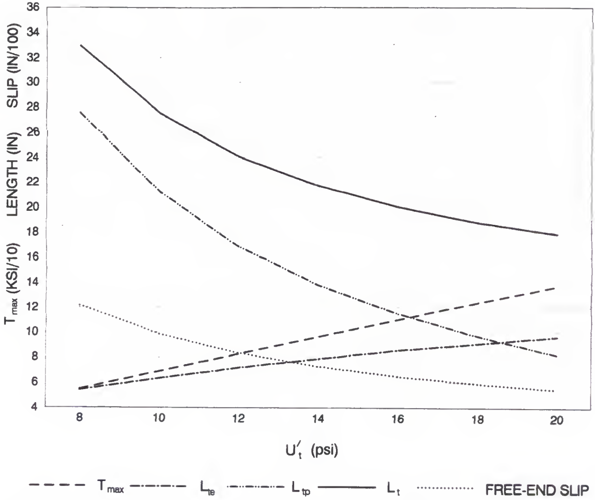


Figure 5.28 Analytical Prediction (2): Effect of Maximum Bond Stress over the Square Root of Concrete Strength, U'_t.

The increase of initial concrete strength from 3,000 psi to 6,000 psi by fixing the U'_t at 17.26 psi results in an increase in maximum bond stress from 919.8 psi to 1,300.9 psi, bond stiffness from 78 K/in^3 to 110.3 K/in^3, and in modulus of concrete from 3122 Ksi to 4415 Ksi (E_c= 57 $(f'_{ci})^{1/2}$) (Table 5.19). In Figure 5.29, the increase in maximum bond stress results in a decrease of the total bond length and slip. The decrease in total transfer length is 5.84", and the slip is 0.0203".

Table 5.19 Analytical Prediction (2) - Effect of Initial Concrete Strength, f'_{ci}.

f'_{ci} (Ksi)	T_{max} (Ksi)	K (K/in^3)	E_c (Ksi)	L_{te} (in)	L_{tp} (in)	L_t (in)	end slip (in)
3	0.9198	78.00	3122	9.50	14.09	23.59	-0.0767
4	1.0621	90.06	3605	9.05	11.87	20.92	-0.0675
5	1.1875	100.69	4031	8.70	10.40	19.10	-0.0611
6	1.3009	110.30	4415	8.45	9.30	17.75	-0.0564

Note: for coated strand when f_{si}=200 Ksi, f_{se}=170 Ksi, E_{ps}=28,400 Ksi, A_c=36 in².

5.4.4 Bond Stress-Slip Relationship

The experimental results (shown earlier in Tables 5.1 and 5.5) show that the bond stiffness, K, generally increases as the concrete strength increases. The relationship between the two is defined by using the t-test in regression analysis. The effect of stiffness is analyzed for coated strands

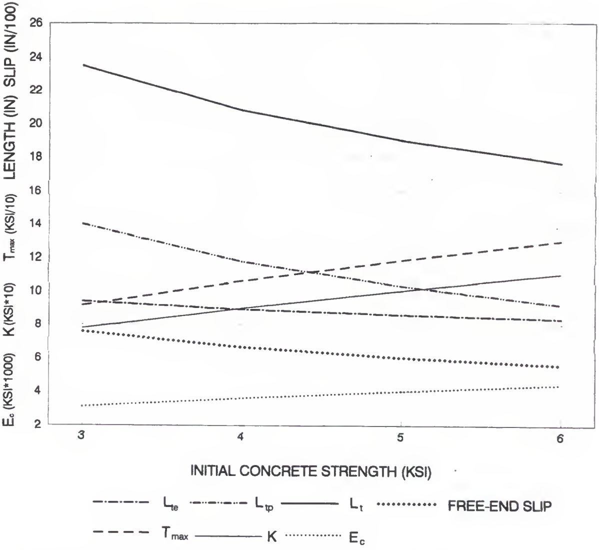


Figure 5.29 Analytical Prediction (2): Effect of Initial Concrete Strength, f'_{ci} .

according to the U'_k value in Equation (5.4). As shown in Figure 5.30, the increase of K results in a decrease in the elastic zone but a small increase in the plastic zone, and consequently a decrease in the total transfer length. When K increases from 55 to 165, the total transfer bond length decreases 5.06", which is generally due to the decrease in the elastic zone of 7.8". A small amount of decrease in free-end slip, 0.007", is observed as shown in Table 5.20.

Table 5.20 Analytical Prediction (3) - Effect of Bond Stress-Slip Relationship, K.

U'_k	K (K/in^3)	L_{te} (in)	L_{tp} (in)	L_t (in)	end slip (in)
0.8	55.09	13.60	9.09	22.69	-0.0672
1.0	68.86	11.50	9.80	21.30	-0.0651
1.2	82.63	10.00	10.32	20.32	-0.0637
1.4	96.41	8.90	10.69	19.59	-0.0627
1.6	110.18	8.00	11.02	19.02	-0.0619
1.8	123.95	7.30	11.27	18.57	-0.0613
2.0	137.72	6.70	11.50	18.20	-0.0609
2.2	151.50	6.20	11.69	17.89	-0.0605
2.4	165.27	5.80	11.83	17.63	-0.0602

Note: for coated strand when f_{si}=200 Ksi, f_{se}=170 Ksi, E_{ps}=28,400 Ksi, A_c=36 in^2, f'_{ci}=4.742 Ksi.

5.4.5 Modulus of Steel

The modulus of steel has not been a significant consideration in analyzing the transfer bond length. Figure 5.31 also shows a minor decrease in plastic bond length,

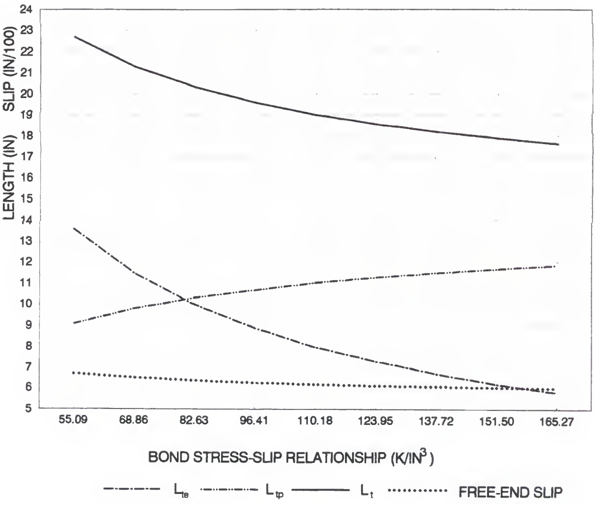


Figure 5.30 Analytical Prediction (3): Effect of Bond Stress-Slip Relationship, K.

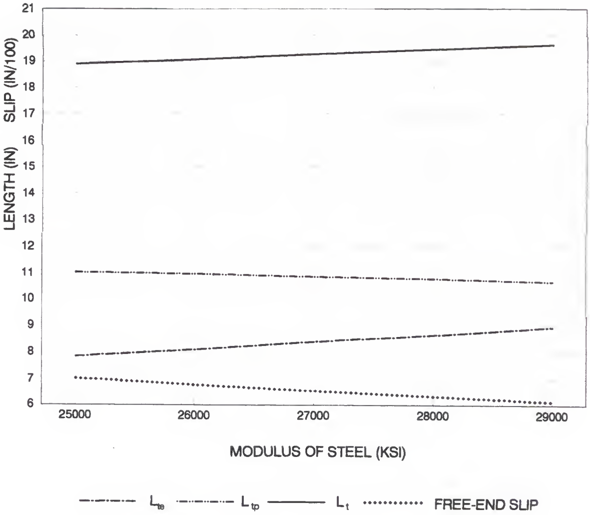


Figure 5.31 Analytical Prediction (4): Effect of Modulus of Steel, E_{ps} .

0.38", but a greater increase in elastic bond length, 1.1"; thus, a total of only 0.72" increase was obtained as Young's modulus increased from 25,000 Ksi to 29,000 Ksi (Table 5.21).

Table 5.21 Analytical Prediction (4) - Effect of Modulus of Steel, E_{ps}.

E_{ps} (Ksi)	L_{te} (in)	L_{tp} (in)	L_t (in)	end slip (in)
25,000	7.85	11.05	18.90	-0.0704
26,000	8.10	10.98	19.08	-0.0679
27,000	8.40	10.86	19.26	-0.0656
28,000	8.65	10.79	19.44	-0.0634
29,000	8.95	10.67	19.62	-0.0614

Note: for coated strand when f_{si}=200 Ksi, f_{se}=170 Ksi, f'_{ci}=4.742 Ksi, A_c=36 in².

5.4.6 Area of Concrete Section

The area of concrete is important when analyzing the bond behavior of a reinforced concrete structure. The effective area in the ACI code refers to the tensile area of the concrete section which is assigned for a tensile steel force. However, the effective compression area has not yet been determined for prestressed concrete. In this study, the entire concrete section is assumed to have a uniform compressive stress which is due to the tensile steel stress.

Different concrete prism sections generally were adopted in previous studies by Dorsten et al. [12], and Cousins et

al. [17,30,32] for the transfer length of the same specific types of steel. However, the effect of different concrete sections has been ignored in these studies. The results in Table 5.22 show that a significant decrease in elastic zone, 5.25", and total transfer length, 4.31", is detected due to the increase in sections from 9 in^2 to 81 in^2. The final relative free-end slip due to steel alone is deducted by the concrete compression strain (Figure 5.25). The free-end slip shown in Figure 5.32 increased slightly by 0.047" because the larger concrete area and less compressive strain produce less reduction in free-end slip due to steel alone than do those of small area and high strained concrete.

The smaller concrete area may cause more compressive strain, which will induce less slip between the concrete and steel (negative effect on slip). This decreased slip will induce less bond stress at the same distance from the end of transfer length (the zero axis of the abscissa). Thus, a smaller concrete area will produce a large elastic zone. It appears that Cousins et al. did not give enough consideration to the effect of concrete area in their analytical and experimental studies. They mentioned that the elastic zones in the transfer test were widely distributed [17].

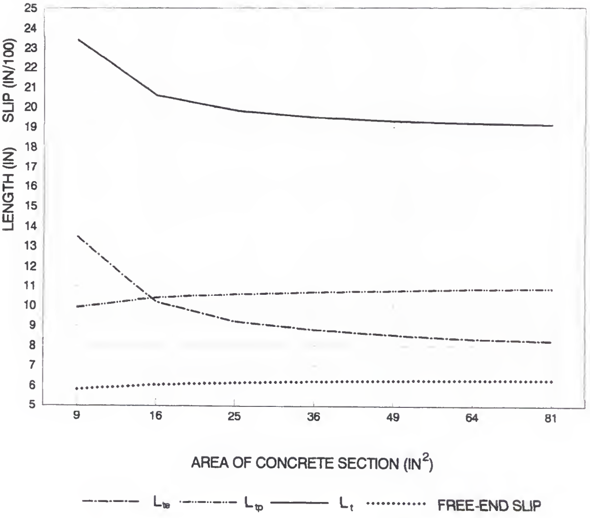


Figure 5.32 Analytical Prediction (5): Effect of Concrete Section Area, A_c.

Table 5.22 Analytical Prediction (5) - Effect of Concrete Section Area, A_c.

A_c (in^2)	L_{te} (in)	L_{tp} (in)	L_t (in)	end slip (in)
9	13.50	9.94	23.44	-0.0586
16	10.20	10.42	20.62	-0.0609
25	9.25	10.61	19.86	-0.0620
36	8.80	10.71	19.51	-0.0626
49	8.55	10.77	19.32	-0.0629
64	8.35	10.86	19.21	-0.0631
81	8.25	10.88	19.13	-0.0633

Note: for coated strand when f_{si}=200 Ksi, f_{se}=170 Ksi, E_{ps}=28,400 Ksi, f'_{ci}=4.742 Ksi.

5.5 Discussion

The experimental and analytical model suggested was developed as a solution to the following questions on the transfer tests:

1) From the past transfer test results, widely distributed transfer lengths have been determined for prestressing strands of the same diameter and type. The simple conclusions of different transfer lengths measured, drawn from the ordinary transfer test, are not sufficient to explain the different test results.

2) The fluctuation of concrete strain within the elastic zone may be one of the most important reasons for the misinterpretation of the transfer test results.

3) The effect of various variables on the transfer length cannot be fully understood by the transfer test alone.

The transfer length itself has been a major concern for the specific type and size of strand in the ordinary transfer test of pretensioned concrete beams. This has led to simple conclusions about the transfer lengths while placing less importance on the various influencing factors' effect. As an example, the analytical method proposed in this study predicts the transfer length as an average of 51.4" for uncoated 1/2" strands, which is comparable to that of Cousins et al. [17], and 27.5" for coated 1/2" strands, which is comparable to that of Dorsten et al. [12] and Lane [33]. These results show a large difference when comparing them with that of the ACI requirement [1]. This difference can be attributed to the following reasons:

1) The elastic zone is more precisely analyzed.
2) Different influencing factors are considered.
3) Different methodology in experimental studies and assumption of analytical studies are used.

The adequacy of the proposed experimental modeling will depend on how closely this model produces the same bond performance within the transfer length in pretensioned concrete beams. The proposed transfer bond stress model was created to describe the same bond state within the transfer length. The following parameters may be considered for the improvement of the suggested model:

1) specimens with confinement steel,
2) different cross section and length of specimens,
3) different releasing rate,
4) different concrete curing conditions, and
5) slip measurement on both sides of the concrete block.

In the analytical studies, the slip was considered as the sum of the positive effect of slip due to steel and negative concrete strain. It was assumed that the entire concrete section has a uniform compressive stress which is due to the tensile steel stress. This assumption generally predicted a small difference when compared with free-end slip measurement in the end of a pretensioned beam because the concrete strain is not actually uniform but increases around the steel.
The measurement of relative free-end slip in Figure 33 also may be influenced by the distance between the steel and the location of the dial gage needle contact point to the concrete surface. In other words, the measured slip will be increased when this distance is greater because concrete negative effect in slip is ignored as the distance increases.

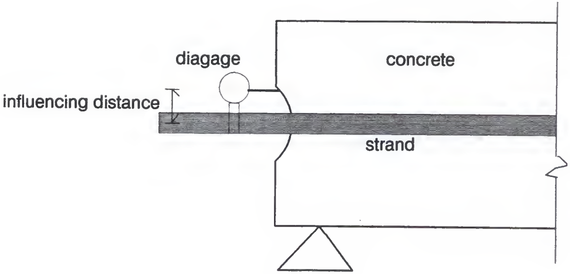


Figure 5.33 Measurement of Free-End Slip.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

The main objectives of this study listed in Chapter 1 were

1) to suggest a new experimental model to obtain the bond properties which are difficult to determine in ordinary transfer tests;

2) to develop a new analytical model to understand the bond mechanism within transfer length;

3) to study the degree of the effect of various variables on critical parameters such as free-end slip, elastic zone, plastic zone, and total transfer bond length; and

4) to study the typical bond behavior of 1/2"-diameter coated and bare strands.

In the ordinary transfer test, the bond stress can be measured only indirectly by measuring the concrete strain. This method has been used for the past several decades; however, the results are too widely distributed to provide a reliable safety criterion for the transfer bond length. In this test, bond stress is measured directly by creating a

similar bond condition within a small portion of the transfer length in a real beam during the transfer of prestressing force. In the experimental study, the characteristic bond properties--maximum bond stress and its relationship with slip--were determined by performing experiments on 1/2"-diameter, grit-impregnated, epoxy-coated and uncoated prestressing strands.

The maximum bond stress and stiffness were analyzed by using linear regression analysis according to the concrete cube strength $(f'_{ci})^{1/2}$ for bare and coated strands. The statistical package program, SAS, was used for the probability of suggested equations. Generally it was found that the t-statistic for testing H0: $\beta_0 = 0$ was not significant when using the intercept model. The no-intercept model provided a fit superior to those for the intercept model. It appeared that the $(f'_{ci})^{1/2}$ was a useful predictor of T_{max} and K in the no-intercept model.

Analytical models for the bond slip, bond stress, steel stress, and concrete stress distributions within the transfer length of a prestressed, pretensioned concrete beam were also developed. Four main stress patterns were given for a better understanding of transfer bond behavior. The maximum bond stress and bond stress-slip relationships were obtained from the prism test with similar boundary conditions in the beam within the transfer length. The transfer length was divided

into an elastic and a plastic zone. The bond stress and slip developed from this point at zero condition. Thus, it was appropriate to define the elastic zone first. The point where bond stress and slip are zero was considered as the zero axis of the abscissa for analysis. The bond stress increased proportionally with the slip to the limit of maximum bond stress within the elastic zone and remained at a constant maximum value within the plastic zone. The total transfer length, stresses, and slip distribution were obtained by defining the location where steel stress was zero due to bond stress.

In the analysis of the results, special consideration was given to the amount of free-end slip, length of elastic zone, length of plastic zone, and stress distributions along the beam in comparison with the ordinary transfer test results by Cousins et al. [17,30,32]. The analytical results were also presented to find the effect of several variables on transfer length and free-end slip. These variables were loss of initial steel stress, the difference between initial and effective steel stress, maximum bond stress over the square root of initial concrete strength, initial concrete strength, bond stress-slip relationships, Young's modulus of steel, and the area of concrete. The experimental and analytical models led to the following conclusions.

6.2 Conclusions

The following conclusions on the bond within transfer length are drawn from the results of this investigation.

1. The suggested test method provides reasonable bond properties within transfer length. The correlation between the results of the transfer test by Cousins et al. [17,32] and the suggested tests shows that this test can give reliable estimates of bonding properties within transfer length. Several important observations have been made from this test.

a) Maximum bond stress for a grit-impregnated, epoxy-coated strand is higher than that of the uncoated strand with the same 1/2"-diameter.

b) The maximum bond stress over the square root of concrete strength, U'_t, is obtained as an average of 6.18 psi for uncoated and 17.26 psi for coated strands. The maximum bond stress of bare strands is approximately 36% of that of coated strands.

c) Bond stress-slip curves show general similarities in the pattern for coated and uncoated strands, but differ in the slope and maximum values. The average maximum bond stress over slip at the point where maximum bond stress occurs is 133.4 K/in^3 for uncoated and 95.5 K/in^3 for coated strands.

d) Compaction has a considerable effect on bond capacities of uncoated strands. It is observed that the U'_t values (4.6 psi and 4.68 psi) in less compacted specimens are much smaller than those of fully compacted specimens.

e) After bond failure, the bond stress cannot reach zero due to slip within the transfer length. Provided there is not a splitting problem, the frictional, Hoyer-effect average bond stress remains at about 270 psi for uncoated strands and 730 psi for coated strands, even after continuous failure, when there is no splitting problem.

2. Linear regression analysis is performed on the test results by using the statistical package, SAS. The following judgement can be made from the t-test in regression analysis.

a) The no-intercept model provides a superior fit to predict the maximum bond stress and bond stiffness.

b) From the no-intercept model in t-tests, it has been determined that the maximum bond stress and maximum bond stress-slip relationships within the transfer length are significantly related to the square root of the concrete cube strength for bare and coated strands. The maximum bond stress is given by the following:

for coated strands,

$$T_{max} = 16.80\sqrt{f'_{ci}} \tag{6.1}$$

and for bare strands,

$$T_{max} = 6.18\sqrt{f'_{ci}} \tag{6.2}$$

The bond stiffness is given by the following:

for coated strands,

$$K = 1.42\sqrt{f'_{ci}} \tag{6.3}$$

and for bare strands,

$$K = 1.78\sqrt{f'_{ci}} \tag{6.4}$$

c) Rust on a bare strand does not seem to be a major influencing factor on bond stress in tests that are run for a duration of two weeks under laboratory conditions.

3. The validity of this analytical study is provided by comparing the results with those of Cousins et al.[17,30,32]. The following are concluded on 1/2" strands from the analytical work.

a) The total transfer length and free-end slip obtained in the proposed analytical study give a close comparison to those of Cousins et al. in bare strands but are longer in coated strands (8.8").

b) The analytical method proposed in this study predicts the transfer bond length as an average 51.4" for uncoated 1/2" strands and 27.5" for coated 1/2" strands.

c) The average elastic zones are 8.8" for bare strands and 15.6" for coated strands. These are an average 17% of the entire calculated transfer bond length for bare strands and 57% for coated strands.

d) The calculated free-end slip averages 0.069" for coated strands and 0.18" for bare strands.

4. In this analytical study, different approaches for bond modelling within transfer length are provided. The analytical work provided here is based on logic and previous and suggested experimental data; hence, it is meaningful. However, there are no means to verify the analytical results by ordinary experimental tests. It is proposed that further research may provide sufficient experimental support to verify the analytical results. The following conclusions are obtained from the analytical study on 1/2"-diameter coated strands.

a) The increase of bond capacity of steel is the most important factor in decreasing the total bond length and free-end slip. The increase of bond capacity is obtained by increasing U'_t value from 8 psi to 20 psi and by

fixing the initial concrete strength at 4.742 Ksi and will produce an increase in maximum bond stress 0.55 Ksi to 1.38 Ksi. The increase of maximum bond stress induces a large decrease in the total bond length by 15.1" and free-end slip by 0.0672".

b) When only the initial steel stress increases from 180 Ksi to 230 Ksi and the effective steel stress remains at 170 Ksi, the transfer length decreases by 9.04" because of a considerable decrease in the elastic zone of 11.15" and a small increase in the plastic zone of 2.11". However, the free-end slip considerably increases by 0.0201".

c) The increase of the initial and effective steel stress is one of most important factors in the increase of the transfer bond length and slip. This increase refers to the increase in effective steel stress. The increase of initial and effective steel stress from 160 and 150 Ksi to 210 and 200 Ksi produces an increase in total bond length of 5.85" and free-end slip of 0.0266" in a coated strand.

d) The increase of initial concrete strength from 3,000 psi to 6,000 psi also shows a decrease in the total bond length of 5.84" and the slip of 0.0203".

e) A 5.25" decrease in the elastic zone and 4.31" in total transfer length are obtained due to the increase in concrete sections from 9 in^2 to 81 in^2. The free-end slip increased by 0.0047" because less compressive strain in concrete will produce less reduction in the free-end slip due to steel only rather than the high strained concrete.

f) The increase of K from 55 K/in^3 to 165.3 K/in^3 results in a decrease in the elastic zone of 7.8" and in a small increase in the plastic zone of 2.7"; consequently, the decrease in total transfer length is 5.06" and free-end slip is 0.007".

g) A slight increase (0.72") in transfer length and end slip (0.009") were observed as the modulus of steel increased from 25,000 Ksi to 29,000 Ksi.

6.3 Suggestions for Further Research

Important subjects requiring further investigations are summarized in this section.

a) The t-tests are performed based on only five tests each for bare and coated strands. More tests are necessary for better estimations of bond properties.

b) The proposed equations are too complex for design purposes and hence may be simplified for its application.

c) The analytical results proposed here cannot be verified precisely by current experimental data; hence more experimental support is necessary in the future.

d) The maximum bond stress and the stiffness, K, in bond stress-slip curves should be varied with the size and surface characteristics of strands. Thus, more tests for different sizes of prestressing strands will be necessary.

e) This proposed study is based on a static analysis. For more accurate estimation, it is necessary to develop an analytical and experimental study for time-dependent fatigue effect.

f) Finally, the suggested method in Chapter 3 can be extended to test the effect of a different releasing method by controlling the releasing rate from the actuator, and to test the effect of confinement by inserting confinement steel on the concrete specimens.

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